Geol. Soc. Malaysia, Bulletin 11, December 1979; pp 1–70.

Tin Distribution Patterns

K.F.G. Hosking[1]

"This tale has seven variations and all cannot be told if time be short".

[East African saying quoted by Holmes (1965, p. 165).]

Abstract: The paper has been written with a view to providing a general background against which the specialised papers of the Symposium can be presented, and also because it is considered that the topic is of fundamental importance both to those concerned with the genesis of the tin deposits and to those whose prime interest is the search for and exploitation of such deposits.

At the risk of creating serious imbalances within the paper the writer has drawn heavily, whenever possible, on his own experiences, believing that by so doing he can make the most useful contribution.

Broadly speaking tin distribution patterns from the global scale to that of the thin and polished section are reviewed, and certain topics which are of particular interest at the present time, together with others that seem to warrant special attention, are high-lighted. More specifically, the major items dealt with are as follows:

I. *The general tin distribution patterns in ordinary rocks, soils, biological material and natural waters.*

II *The broad world and continental distribution patterns of the tin deposits.*

The relationships between types of tin deposit and their age. The significance of tin deposits of distinctly different ages in the same province. World tin belts. Tin distribution patterns and plate tectonics.

III. *Tin patterns within tin provinces*

A. The tin-bearing species: further considerations.

B. The classification of the tin deposits.

C. Mineralogical aspects of the patterns of primary tin deposits.

D. Relationships between tin distribution patterns and igneous rocks.

E. Tin distribution patterns in the surface and near-surface environments in tin provinces.

The major conclusion that stems from this review is that we still have much to do before we arrive at a real understanding of the genesis and distribution of the tin deposits. We still do not have a plate tectonics model for any of the tin provinces that is generally acceptable, although great strides are being made in the right direction. We have still much to resolve concerning the granite/tin problem. The sources of the tin which occur in the primary deposits are still matters of dispute, as is the chemistry of the tin-transporting and tin-depositing systems. The list of defects could be enlarged.

Perhaps the most satisfying outcome is that we are presently much more aware of the problems that need to be tackled in order to make great strides towards our understanding of the tin deposits, and to be aware of the problem is to be half-way towards solving them.

INTRODUCTION

The Cornish miner, when talking of tin, was wont to say 'where it is, there it is'. To him its distribution was 'a riddle wrapped in a mystery inside an enigma*'. Today,

[1] 1B, Penlu, Tuckingmill, Camborne, Cornwall, TR14 8NL, ENGLAND.

*Quote from speech of Sir Winston Churchill given in the House of Commons, London on 22nd Feb. 1939.

in spite of endeavours the riddle is not solved, but we are closer to the solution, or a possible solution. It is not conceivable that a unique solution will ever be arrived at if for no other reason than it is unlikely that we shall be able ever to obtain direct proof of the source of the tin. In this paper it is my object to describe and discuss tin distribution patterns of all sizes, from those that can be conveniently presented on a map of the world that occupies the page of a paperback book, to those occurring within a given sample of tin-ore and which may require the establishment of the distribution of the elements over very small areas by means of the electron microprobe. I shall also record and comment on some of the attempts that have been made to account for one feature or another of these distribution patterns.

THE GENERAL TIN DISTRIBUTION PATTERNS IN ORDINARY ROCKS, SOILS, BIOLOGICAL MATERIAL AND NATURAL WATERS

In common with many other elements, some tin, often in small concentration, probably occurs in all the Earth's solid and molten units that are available for study, together with the waters and gases of the Earth and the plants and animals that populate this planet. However, excepting locally in the tin-fields the concentration of tin in any naturally-occurring medium is usually very low and the Clarke of the element is only 2–3 ppm. (Wedepohl, 1969).

When considering the distribution of those tin deposits which are of economic interest now, or which are likely to be of economic interest in the forseeable future, it is necessary to consider all possible sources of the tin in these deposits. So it is relevant to briefly present some data relating to the abundance of tin in naturally occurring things of geological interest. For a much more detailed coverage of this topic one may consult Wedepohl (1969), Hamaguchi *et al.* (1964) and Mulligan (1975).

The abundance of tin in rocks appears in Table 1.

TABLE 1

THE ABUNDANCE OF TIN IN ROCKS (PPM).
(AFTER WEDEPOHL, 1969)

Rock type	Authors		
	Onishi & Sandell (1957)	Hamaguchi *et al.* (1964)	Horn and Adams (1966)
IGNEOUS			
Silicic rocks	3.5	3.6	
Intermediate	1.3	1.5	2.5
Mafic	1.2	0.9	
Ultramafic	0.5	0.35	
SEDIMENTARY			
Shale	4		4.12
Sandstone			0.115
Carbonate			0.166
Oceanic clay			0.5
Red clay (Pacific)		4.9	
Red clay (Japan Sea)		4.	

Concerning the abundance of tin in igneous rocks the most important fact to note is that it increases from the ultrabasic to the silicic (granitic). It is to be noted that this trend is based largely on the analysis of intrusives, but it is also suggested by a rather limited number of results of analyses of corresponding suites of effusives. This trend, as Mulligan (1975, p. 9) observes, 'in conjunction with the worldwide association of tin with granitic rocks, is the main evidence for the conclusion that tin is concentrated in the late products of magmatic differentiation'. However, the geochemical and other aspects of the relationship between tin and granitoids is dealt with in a later section for convenience.

When considering such topics as the genesis and distribution of tin deposits it is well to remember that tin occurrences, although rare, may be present in alkaline rocks. Such tin as may occur in alkaline rocks may be entirely held in alkaline ferromagnesian species, particularly in riebeckite and aegirine, and in astrophyllite and accessory minerals. Occasionally such rocks may contain minerals in which tin is an essential constituent. Thus, nordenskioldite ($CaSn(BO_3)_2$) was first reported from a Norwegian nepheline syenite pegmatite, whilst sorensenite ($Na_4SnBe_2Si_6(OH)_4$), 'a hydrothermal mineral' was found in the Ilimaussaq alkaline complex of Greenland. It is also not without interest to note that according to Gerasimovskiy and Borisenok (1968) this alkaline complex of Greenland has a tin content that ranges from 35 to 370 ppm, with a mean of 112 ppm, whilst the neighbouring alkali granite had a mean tin content of only 49 ppm. Mulligan (1975, p. 9) records that the Teslin area, Yukon, provides a similar state of affairs. There the syenitic member contains 25 ppm tin whilst the nearby granitic bodies contain only 5 ppm of the metal.

Information concerning the tin content of sediments and metasediments is meagre. Table 1, provides some idea of the concentrations of tin that one might expect to find in the rocks in question in areas removed from tin mineralised districts. It seems to me reasonable to expect shales and other sedimentary rocks that are generated from the detritus of tin provinces to be, on occasion, distinctly stanniferous. Stanniferous placers, ancient and modern, are end-members of a classification of sedimentary deposits according to their tin content. Other sediments that cannot claim to be called stanniferous placers must, on occasion, contain sufficient tin possibly for them to be converted by metamorphic processes of one sort or another, or by magmatic invasions, to tin deposits of economic importance. I cannot believe that tin released into the drainage systems by superficial processes can never more take part in those geochemical syntheses which result in the development of new hard-rock tin deposits. Only by postulating the mobilisation both of released tin and of anomalous concentrations of tin in hard-rocks can I find an acceptable explanation for the presence of primary tin deposits, of two or more widely differing ages, in a given metallogenetic province. I shall return to this theme later.

Hawkes and Webb (1962, p. 373) state that the average tin content of soils is 10 ppm. I think that all that this figure means is that by and large soils are not particularly rich in tin. In stanniferous provinces the tin content of a given soil may increase rapidly from a very low figure to something in excess of one per cent as a sub-outcropping or outcropping primary tin deposit is approached. Also in such an environment, and particularly in the vicinity of a sub-outcropping hard-rock deposit, the tin content may vary greatly from one horizon to another at a given sampling point.

Tin is usually in low concentration in plants (although, as will be seen later, there are some notable exceptions) even when the soil in which they are growing is well endowed with the element. Thus, in the Gunnislake district of the Southwest of England Millman (1957) found that species of *Quercus*, *Betula*, *Fagus* and *Salix*, that were growing in soils containing up to 250 ppm tin, only contained 1 ppm of the element in question. Millman thought that the limited uptake was due to the fact that cassiterite is not more than very slightly soluble in the solvents available in the superficial environment and that in an area in which the much more soluble tin-bearing sulphides were much in evidence plants might contain much higher concentrations of tin than were in those which he had investigated. That plants may contain much greater concentrations of tin than those investigated by Millman has been established by a number of workers. Thus, Ivashov and Bardyuk (1967) reported that the ashes of certain species of plants that were growing over ore bodies contained up to 0.3 per cent tin and this was more than five times the amount found in the anomalous soils. Sarosiek and Klys (1962) found that *Calluna vulgaris*, *Gnapthalium sylvaticum*, *Sempervivum soboliferum*, *Silene inflata*, *Tanacetum vulgare* and *Quercus sessilis* accumulated tin and that the average metal content in the ashes of these plants was 46 ppm.

In view of the above observations it is not surprising that Goldschmidt (1954) found that tin was enriched in some forest litter and in some coal ashes. Of course, the tin content of such material may, in some environments, be due to discrete particles that were washed into the zones of accumulation or that were blown on to the plants when they were growing. That plants can be seriously contaminated by dust and by rain splash is beyond doubt, and adequate cleaning of such material before analysis can be very difficult. For this reason any report of the tin content of plants from areas near operating mines, exposed tin deposits and tin smelters should be questioned.

To turn to the sea, according to Nichols (1959) the ash of some marine plankton has a tin content that varies from 1 to 90 ppm.

In natural waters the concentration of tin, according to Wedepohl (1969) varies from 0.03 to 0.09 ppb. However, Udodov and Parilov (1961), who analyzed 4278 water samples, including some from ore deposits, from Siberia, found that tin occurred in 340 of the samples and that the average tin content was 0.09 ppb. The same workers, as a result of dividing the average tin content in water (weight percent) by the Clarke in rocks, which they concluded was 0.0003 weight per cent, obtained the figure of 3.10^{-5}. This figure indicated to them that the migration capacity of tin in the environment in question was very slight. Apropos of this it is relevant to note that, according to Schuiling (1968, p. 541) cassiterite, by far the commonest of the primary tin species, is only very slightly soluble in a typical natural surface water, and that at 25 °C and one atmosphere pressure it is 10^{-15}. Schuiling warns that changes in the system, for example, the addition of chloride ions, may cause the total solubility in water to be higher because of the formation of complex ions.

To what extent cassiterite or any of the other much rarer primary and secondary tin species are attacked by the organic complexes present in the soil is at present unknown, nor do I know what happens to any of the tin minerals if they find themselves in a very acid environment such as might develop, for example, by the oxidation of pyrrhotite. I do know that coarse cassiterite that occurs in pyrrhotite veins which are undergoing active oxidation, and which have been exposed in some of the mines not far from Kuala Lumpur, shows no obvious signs of attack.

Although it is clear, as noted earlier, that tin is mobilised in soils, sometimes apparently to quite a surprising degree, I know of no work that proves that in a given instance the mobilised tin has definitely been derived from a given mineral or minerals.

Varlamoffite, or something akin to it, is the usual tin product that results from the oxidation of those sulphides in which tin is an essential component and it may also be the tin end-member that results from the breakdown in the zone of oxidation of other tin-bearing minerals, regardless of whether the element in question is an essential or non-essential ingredient. Varlamoffite is certainly more soluble in HCl and H_2SO_4 than cassiterite is, and it may be appreciably more soluble than cassiterite in some or all of the organic soil solvents. Possibly some cassiterites, because of differences in their chemical composition, are more soluble than others in the naturally occurring solvents of the superficial environment, but I know of no evidence in support of this other than the claim of Jones (1967) that an appreciable percentage of the cassiterite in the ore from the Pinyok Mine (Thailand) is acid soluble. The soluble fraction is, in Jones' opinion, that fraction that occurs as very small and thin crystals. I find this view difficult to accept. I prefer to think that any differences in solubility are due to compositional differences and the so-called soluble cassiterite may, in fact, have been varlamoffite that was derived from the decomposition of malayaite. When Jones was writing he was unaware of the presence either of malayaite or varlamoffite in the Pinyok ore.

To return to the question of tin carried by surface waters, it was long ago thought that in favourable environments cassiterite might be precipitated from river waters. Collins (1881) reported that a portion of a deer's antler that was recovered from the stanniferous placers at Pentewan (Cornwall) contained, on analysis, 2.62 per cent SnO_2 and he believed that the tin had been deposited as the oxide from solution. In later years I examined the remainder of the antler and found that it contained only trace amounts of tin. Most samples analyzed contained less than 10 ppm Sn although two external samples contained 296 ppm of the element. Furthermore, examination of thin and polished sections of portions of the antler failed to reveal the presence either of cassiterite or of any other tin species. It was concluded that the tin reported by Collins was probably in the form of grains of cassiterite that had been washed into the Haversian canals, etc., for a limited distance from the broken end, and that this cassiterite-contaminated part was that which Collins had analyzed (Hosking, 1957–8).

Although there is little doubt that the soluble tin content of the waters of natural drainage systems is usually, and probably always, very low, there is the possibility that in these systems tin may be transported as a component of colloidal particles. Apart from the generation of such colloids by chemical processes operating in the zone of weathering it may be that tin-containing colloids are also generated by mechanical means. In support of this I recorded (Hosking, 1965) that a crystal of white cassiterite from Ayer Hitam (Selangor), when placed between several sheets of newspaper and hit with a hammer, provided a powder that when placed in distilled water yielded a fraction that remained in suspension for several days and was eventually flocculated by the addition of aluminium sulphate. In my view this fraction was in the colloidal state. Similar fractions are, I think, likely to be produced by abrasion in streams containing, cobbles, pebbles, etc., which are moving, and/or which are being abraded by sand, and on which cassiterite is exposed. I do not know to what extent such colloids might be stabilised in any of the drainage environments but I think that on occasion they may become stabilised. I suspect that the 12–16 ppb Sn occurring in the water of the Red

River, and two miles below the mill of South Crofty tin mine, in Cornwall, which was discharging slime tailings into the river when the analyses were carried out, was largely present in colloidal particles (Hosking, unpublished studies.)

In spite of the fact that Boyle (1969, p. 25) councils that water surveys are not suitable for geochemical prospecting for tin deposits, because of the slight concentrations of the element likely to be encountered in the water, he does suggest that wad, limonite, humic and other precipitates at the orifices of springs may be enriched in tin and that such deposits should be analyzed for tin and other pathfinder elements (e.g. W and Li) as they might facilitate the search for tin deposits in some areas. Unfortunately, Boyle provides no details of the tin content of such deposits, nor do I know of any published information on the subject. It seems to me that this is a topic worthy of further investigating and that the deposits likely to be the richest in tin are those in stanniferous provinces that are associated with hot springs and particularly those within active or recently active volcanic areas. It is known that in some volcanic areas tin has been transported in the gaseous state and deposited in the sublimates. This has happened, for example, at Showa Shinzan, Hokkaido (Japan), Etna (Sicily) and in the Valley of Ten Thousand Smokes (Alaska) according to White and Waring (1963). In addition, I have been privately informed recently that a sample of sediment taken from a hot spring in Northern Sumatra contained 100 ppm Sn. No record is yet available of the tin content of the water of this hot spring, but it is of interest to record that the tin content of Japanese hot springs ranges from 0.1 to 0.5 ppb.

Sea water contains an average concentration of 0.72 ppb tin (Mulligan, 1975) and according to Goldschmidt (1954) the element is possibly in the form of the stabilised chlorostannate ion, and adsorption of the tin from both surface waters and sea water may be responsible for little or much of the tin in the finer-grained sedimentary rocks. Apropos of this Durasova (1967) is of the view that in a marine environment illite might adsorb tin.

Finally, when considering this 'background' tin distribution pattern it is relevant to consider how the tin occurs in the rocks.

The minerals that contain tin may be divided into two groups. The first group contains those species in which tin is an essential component and the second consists of those minerals in which it is a non-essential component. The former group contains all the species which are now of economic importance as sources of tin, and of these cassiterite is far and away the most important. The tin-bearing sulphides are of limited importance now but they may become more important in the future. Of the tin-bearing sulphides, those that may be loosely called the members of the stannite group are the commonest and economically speaking hold pride of place amongst the tin-bearing sulphides. Malayaite (CaO. $SnO_2.SiO_2$) is also a member of the first group and may possibly become, at least at Pinyok (Thailand) a subsidiary source of tin. The other primary members of the group are of little more than academic interest in that they tend to occur in small concentrations and are of rare occurrence. Pabsite (BaO. SnO_2. SiO_2), for example, has only been recorded from San Benito County, California. Generally the tin-bearing silicates and borates, which have a penchant for skarn environments, seem to require very special circumstances for their development.

Varlamoffite, possibly largely hydrated tin oxide, is a 'mineral' derived from the decomposition of other tin-bearing species and will be returned to below.

In this group is also to be found the stannides of the platinum group of metals which are rare, but of considerable academic interest in that they occur in the copper/nickel/platinum metals deposits that are spatially and probably genetically related to basic igneous rocks. They are found, for example, in the Merensky Horizon of the Bushveld Igneous Complex and in the Insizwa deposit of South Africa and in that at Noril'sk (U.S.S.R). Native tin, is another very rare species found, but not solely, within such deposits.

Members of the second group, in which tin occurs as a non-essential component, may be divided into two sub-groups. In the first, which includes oxides and silicates, tin behaves as a lithophile element whilst in the second, which consists of sulphides, it behaves as a chalcophile element. In the case of the silicates and oxide-type minerals ionic bonding is all-important whilst in the case of the sulphides covalent bonding rules the day. The rules of Goldschmidt (1937), Ringwood (1955a & b) and Nockolds (1966) have progressively improved Man's ability to predict and understand the presence of non-essential elements in minerals. For reasons of space, and because they are readily available in the literature, these rules will not be dealt with here. It is sufficient to say that application of these rules goes a long way towards understanding why quartz is tin-deficient, why the feldspars never have more than a very low concentration of tin, and why biotites and amphiboles, particularly the late-formed ones, may contain comparatively high concentrations of the elements, as may such igneous rock accessory minerals as magnetite, ilmenite, rutile, apatite and allanite and such ore minerals as columbite/tantalite, wolframite, galena, sphalerite and chalcopyrite. In a number of the minerals mentioned immediately above tin in excess of that which can be accommodated in the lattice of the host species exists as exsolution bodies of a discrete tin species. Thus, for example, exsolution bodies of cassiterite may occur in magnetite, columbite/tantalite, and ilmenite, whilst 'stannite' exsolution bodies may be found in sphalerite and chalcopyrite.

In the zone of oxidation unstable minerals containing tin as an essential component or as a non-essential one in the lattice and/or as exsolution bodies of tin species, may suffer little or much decomposition. The history of destruction of such minerals is subject to considerable variation and is dependent on many factors such as climate, topography, the textural relationship between the tin-bearing species and its companion minerals and the composition of the latter. Under conditions approaching the optimum for decomposition, the tin from the stannite group of minerals reports, at least in part, as varlamoffite having passed through an intermediate stage, at least in some instances, as berndtite (SnS_2) (Clark, 1969.) It is possible that some of the tin liberated by 'stannite' may escape from the system in solution, but I don't think this has been demonstrated. Some of the liberated tin may, on occasion, report as cassiterite as was the case at the Sardine Tin Mine (Edwards and Baker, 1954).

Much less is known of the intimate behaviour of other unstable tin-bearing minerals in the zone of oxidation, but it seems reasonable to believe that some of the tin converts to varlamoffite, or something akin to it, whilst some may be fixed as cassiterite, and possibly some may migrate in solution into the soil and/or the drainage system. Perhaps the mobile fraction, which must exist in some soils, is largely due to the solution of varlamoffite.

Cassiterite is unlikely to suffer marked chemical attack, in my view, in the superficial environment, and in a given situation little or much of it may be ultimately liberated from its primary host.

However, there is no doubt that cassiterite, particularly when it occurs as a minor constituent in composite grains composed largely of low specific gravity inert species, such as quartz and muscovite, may be transported via even long drainage systems to the sea. So there is a progressive removal of tin from the consolidated rocks, igneous and others, to the unconsolidated surface and submarine rock cover. Some of the liberated cassiterite may concentrate in placers of economic interest and some is distributed in low concentration in other sedimentary deposits. Such cassiterite may survive through more than one sedimentary cycle. But is this all that can happen to it?

THE BROAD WORLD AND CONTINENTAL DISTRIBUTION PATTERNS OF THE TIN DEPOSITS

Having looked at the background tin pattern of the world one can turn one's attention to the world and continental patterns of distribution of those tin deposits that are of economic interest. As a prelude it is necessary to consider first the broad temporal aspects of the theme.

Primary tin deposits have been developed from the Precambrian to the Tertiary. Pereira and Dixon (1965, pp. 518–520), as a result of a statistical study, claim that known tin deposits become progressively more plentiful, and economically more important, on ascending the geological time-scale from the Pre-Cambrian to the Tertiary. This, to them, suggests that tin is "progressively concentrated by granitisation processes". Watson (1973) agrees broadly with the views of Pereira and Dixon (noted above) and states that "although cassiterite occurs as an accessory mineral in pegmatites dated at 2.6–2.7 b.y. in West Africa and Rhodesia, forms detrital grains in the Dominion Reef Formation of South Africa (2.7–2.8 b.y.) and is associated with the Bushveld granites (ca. 1.9 b.y.), tin mineralisation of economic importance was largely confined to younger periods". Watson further observes that "about a billion years ago mineralisation in two rather different settings marked the widespread incoming of tin, tungsten and their associates to the record. The Karagwe-Ankole or Kibaran mobile belt of Africa, which reached the terminal stages of orogenic activity at this time, was characterised by abundant granites and by metamorphism of a low-pressure facies series usually attributed to the operation of a high geothermal gradient. Tin-tungsten deposits are associated with late orogenic (0.9 b.y.) granites at various localities from Uganda to South-West Africa. In the Rondonia district of western Brazil tin deposits are clustered near a group of high-level anorogenic granites dated at about 0.9 b.y. and emplaced in a basement of granite and gneiss".

"These tin-bearing assemblages share many of the characteristic features of younger tin deposits. The Karagwe-Ankole belt, like the tin-bearing Hercynian belt of western Europe, was a zone in which a steep geothermal gradient developed; it was not subjected to a major influx of mantle-derived igneous material, and some, at least, of the mineralised granites appear to represent remobilised basement granites. The granites of Rondonia have much in common with the Mesozoic Younger Granites of Nigeria, which are strongly fractionated high-temperature intrusions emplaced in a granitic or gneissose basement. These relationships render it unlikely that the appearance of concentrations of tin, tungsten and allied metals about a billion years ago was connected directly with the influx of material from the mantle.

"The well known evidence of repeated mineralization in tin provinces such as those of Nigeria and western South America shows that the later phases were commonly richer than the earlier......... With the remarkably late start to effective tin mineralization, this evidence suggests that recycling within the crust was an inefficient process, which worked best in terrains previously enriched in the metals".

Routhier (see Laboratoire de Geologie Appliquee, Universite de Paris, France, 1973) is also a champion of the recycling view. He believes that "concentrations of certain metals occur repeatedly in an area, or rather in a 'prism' of the earth's crust at different periods and with different types. Each concentration inherits from a geochemical stock more or less dispersed or concentrated at earlier periods. This results in a **remanence** or **permanence** of the metals considered, in the 'prism' of the crust where they are more abundant than the Clarke". Amongst a number of examples in support of his theses he mentions the Bolivian tin belt. Regarding it he writes 'Everyone knows the Bolivian type of tin deposit, linked to the Tertiary volcanism and subvolcanism. However, hardly any attention has been drawn ..... to other concentrations in rocks of very different ages; in Bolivia .... in **lower Cretaceous** sandstones—in relation with **lower Jurassic** plutonism—in **Devonian** quartzites".

And, north of Bolivia, the Rondonia State (Brazil) deposits are associated with ring dykes, which are very comparable to those of Nigeria, but which are probably much older: 950 m.y.".

Routhier concludes "In the end, going back in time, these heritages and remanences lead us very often, and as it were inevitably, to the ideas that portions of the crust and mantle were geochemically differentiated ever since their origin".

Schuiling (1968, pp. 539–540) claims that "if the tin deposits are divided into five groups, namely, into those associated with volcanic rocks, with subvolcanic dykes and plugs, near the roof zones of granites (in greisen and skarn deposits), within granites and in pegmatites, a striking frequency of occurrence with geological time shows up. Whereas in the Tertiary the association of tin deposits or groups of tin deposits with volcanic rocks is predominant, there is a shift towards greisen, skarn and other contact deposits in the Mesozoic, towards deposits in the granites in the Palaeozoic and towards pegmatitic deposits in the pre-Cambrian". This difference can most simply be explained, in Schuiling's view, on the basis of the level of erosion. This at least suggests that all types of tin deposits may have been developed to the same degree from the time when tin deposits were first generated. It is certainly reasonable to expect that generally the deposit that has developed nearest the surface is likely to have the shortest life, so it is at least likely that in a given tin province in which all Schuiling's groups occurred and in which all the groups were more-or-less of same age, that the first to be destroyed would be those associated with volcanic rocks and amongst the last to disappear would be the stanniferous pegmatites. Given time all the primary deposits might be destroyed. So the patterns which have been analyzed by Pereira and Nixon, and Watson, which are mentioned earlier, and which have persuaded them that the tin depositional patterns have evolved throughout geological time may, in fact, not be the original ones but only the remains after denudation has taken its toll. In spite of this, Watson's views may still be fundamentally correct, but neither they nor those of Routhier, noted above, are acceptable to some of those who endeavour to explain the tin distribution patterns in terms of Plate Tectonics. Halls (1974, p. 493) for example, remarks that 'geologists have accounted for the limited distribution of tin deposits in terms of the primeval enrichment of certain parts of the continental crust by an unknown process at an early stage in geological history, suggesting that these parts had retained their tin-enriched character throughout the subsequent stages of their geological evolution. But recent developments in thinking have led to more sophisticated propositions regarding the genesis of tin ores which place them in perspective with other geological processes."

So it is pertinent to consider some of the various views ofthe genesis of tin deposits that have been proposed by the plate tectonicists, of whom Halls is one, but before doing this it is necessary to note the Earth's spatial distribution pattern of tin deposits.

Figure 1 (after Sainsbury, 1969) shows the rather spotty distribution of the tin deposits of the world. At least three-quarters of the world's tin reserves are closely associated with granitoids that are distributed in mountain belts. Notable amongst these belts are those formed by the western mountains of the Americas that margin the Pacific Ocean and are here and there dotted by tin deposits from Alaska to Argentina, and the Asian belts of which, economically speaking, the most important is that stretching from north-west Thailand, (or even beyond) to Belitung and possibly into Borneo. These orogenic deposits may, or may not parallel and lie close to present oceanic coastlines, and within a given belt tin deposits of a number of different types, and of a number of distinctly different ages, may occur. Not surprisingly, within a given stanniferous belt granitoids of a number of distinctly different ages may also be found. Of these granitoids, only those of certain given ages and compositions may have tin deposits spatially so associated with them that there is some reason for believing that a genetic relationship might exist between ore-body and granitoid. On occasion the tin belt is paralleled by metal provinces in which other metals are dominant, and the best example is provided by the orogenic belts which parallel and are close to the Pacific coast of the Americas. There, as recorded by Sillitoe (1972, p. 813) the "metal provinces are aligned approximately parallel to the continental margins, and, despite irregularities, a general pattern of provinces comprises the following sequence from west to east: Fe; Cu (with some Au and Mo); Pb, Zn, and Ag; and in some regions Sn or Mo".

In marked contrast to the orogenic deposits are the anorogenic ones. These latter deposits, and the granitoids which are closely spatially associated with them, are not related to mountain building processes. The Rondonia (Brazil) tin deposits fall into this group and possibly, as Halls (1974, p. 493) suggests, those of Transbaikalia (U.S.S.R.) and of Mongolia also fall into the same category. However, most of the known anorogenic deposits are to be found in Africa and as Halls (1974, p. 493) remarks "they are found widely spread from southern Morocco and the Hoggar massif of Southern Algeria to the Adrar des Iforas in Mali and from the Air and Zinder area of Niger to the major deposits of the Jos Plateau in Nigeria. They also occur at Sabaloka in northern Sudan, in southeast Egypt and in the Damaraland province of South-West Africa".

As Halls further observes "the possibility exists that further anorogenic deposits may remain, as yet undiscovered, in poorly explored Precambrian .... terrain in other parts of Brazil, Africa, the Soviet Union and possibly also in the interior regions of Australia and India".

By plotting all known economic or marginal and uneconomic occurrences of tin minerals in the Americas, Europe and Africa, Schuiling (1968, p. 531–533) demonstrated, in a very convincing manner "that tin occurrences are not evenly distributed over the continents, but that they are concentrated in elongated zones known as tin belts". He was aware that "the drawing of the boundaries is rather

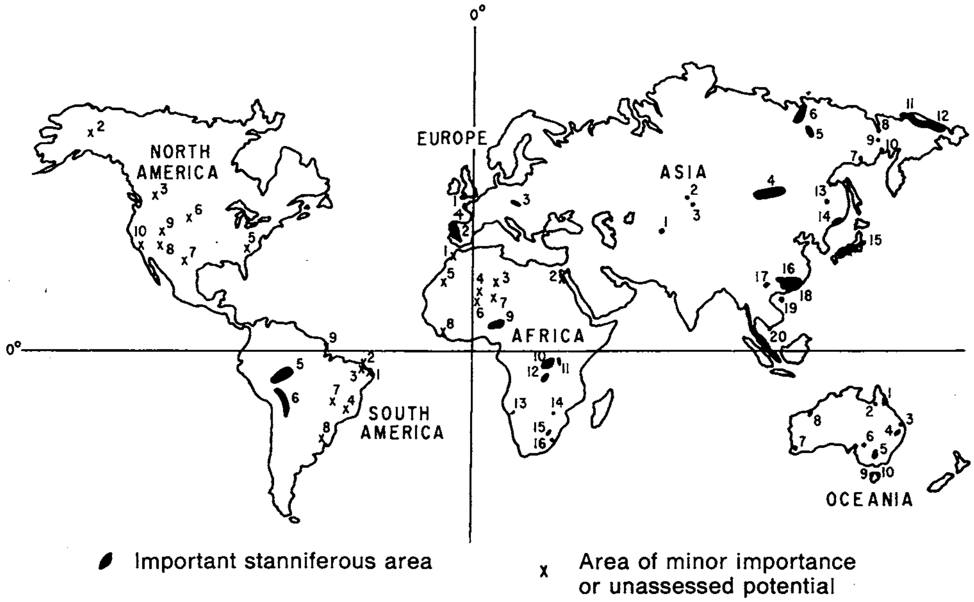


Fig. 1. Major stanniferous regions of the world (After Sainsbury, 1969).

NORTH AMERICA

1. Seward Peninsula, Alaska
2. Manley Hot Springs, Alaska
3. Sullivan mine, British Columbia, Canada
4. New Brunswick area, Canada
5. Southern Appalachian area
6. Black Hills area, South Dakota
7. Franklin Mountains, Tex
8. Black Range district, New Mexico
9. Climax mine, Colorado
10. German area, California

SOUTH AMERICA

1. Rio Grande do Norte-Parafba, Brazil
2. Northeast Ceará, Brazil
3. Central Ceará, Brazil
4. Eastern Minas Gerais, Brazil
5. Rondonia-Tapajos, Brazil
6. Tin belt, Bolivia
7. Ipameri, Goiás, Brazil
8. Eneruzilhald, Brazil
9. Amapá area, Brazil

EUROPE

1. Cornwall, England
2. Portugal and Spain
3. Erzgebirge, German Democratic Republic (East Germany) and Czechoslovakia
4. France

AFRICA

1. El Karit area, Morocco
2. Igla, Nuweibeh Abu, and Dabbab el Mueilha areas, United Arab Republic (Egypt)
3. Djilouet area, Algeria
4. Tamanrasset area, Algeria
5. Bir Oumgreine area, Mauritania
6. Iforas area, Mali
7. Air district, Niger
8. Tawalafa area, Sierra Leone
9. Jos Plateau, Nigeria
10. Maniema area, tin belt, Democratic Republic of the Congo
11. Rwanda, Burundi, Uganda, and Tanganyika (Tanzania)
12. Manono-Kitololo mines, Katanga, Democratic Republic of the Congo
13. South-West Africa
14. Southern Rhodesia and Nyasaland
15. Rooiberg-Leeuwport area, Republic of South Africa
16. Warmbad area, Republic of South Africa

AUSTRALIA

1. Herberton-Cooktown area
2. Croydon area
3. Stanthorpe-Ballandean district
4. New England district
5. Mount Tallenburg-Albury-Eldorado belt
6. Barrier Range
7. Southwest Western Australia
8. Northwest Western Australia
9. Northwest Tasmania
10. Northeast Tasmania

ASIA

1–14. Siberia, U.S.S.R.
  1. Altai Mountains
  2. Naryn, Kazakstan area
  3. Kalba, East Kazakstan
  4. Transbaikal (Zabaykal'ye) area
  5. Xana-Adycha area
  6. Ege-Khaya-Deputatskiy region
  7. Ust'-Omchug, Batugychag area
  8. Bilibina area
  9. Kolyma area
  10. Galimyy area
  11. Krasnoarmeyskoye area
  12. Iul'tin area
  13. Kbingansk area
  14. Lifudzin-Khrustal'nyy area
15. Honshu Island, Japan
16. Kwangsi-Kwangtung-Hunan Provinces, China
17. Kochiu area, China
18. Coastal zone, China
19. Hainan Island, China
20. Malay Peninsula

subjective, and different people provided with the same set of data would probably come up with slightly different patterns ....". He also appreciated that geochemical studies of the type employed by Burnham (1959) (who established the limits of metallogenetic provinces in the Southwestern United States and Northern Mexico by determining the concentrations of various trace elements, including tin, in samples of chalcopyrite from many localities) would serve to refine the definition of the belts. By replotting the tin belts on the best fit map of the continents on either side of the Atlantic Ocean, that was devised by Bullard *et al.* (1965), Schuiling revealed what he termed a number of remarkable coincidences. Of these, perhaps the most remarkable coincidence is that the east Brazilian belt and the South-west Africa-Nigerian belt appear to be displaced parts of what was originally a single unit, but the reconstruction is of further interest in that, as Schuiling (1968, p. 544) observes "it is apparent that at all points where belts strike into the oceans, there is evidence that they might have been continuous in an orderly fashion".

In recent years great advances have been made towards a better understanding of ore-genesis by considering the problem in the light of plate tectonics. In a paper such at this it is out of the question to provide details of the different plate tectonic models that have been proposed for various of the tin provinces of the world. One can only briefly concern oneself with some of the mechanisms that have been proposed to account for the tin in such provinces.

Sillitoe (1972) proposed the following elegant theory to account for the tin and other metal provinces that parallel each other and the continental margin of Western America that have been referred to earlier in this paper. Briefly, he suggested that post-Palaezoic metal provinces of the area in question are related to subduction zones that were active during the Mesozoic and early and middle Cenozoic, and that are still locally active along the belt. He is of the view that 'much of the metals contained in post-Palaeozoic magmatogene ore deposits of western America were carried eastward in oceanic lithosphere from the East Pacific Rise from where they originated and were thrust beneath the continents along inclined Benoiff zones. The subducting plate with its load of unconsolidated sediments, was subject to partial melting, and in such a way that different ore metals were liberated at different depths. This view was inspired by the fact that there is an increase in the potash to silica ratio of andesites eastward from the circum-Pacific continental margin.

In the view of Sillitoe the metals released by the partial melting were incorporated in ascending bodies of calc-alkaline magma. "The metals attained high crustal levels as components of the magmas, finally to be concentrated in fluid phases associated with the roof zones of intrusive masses and also with comagmatic extrusive rocks." Sillitoe takes this view because of the close temporal and spatial relationships between various ore deposits and igneous rocks that have been established in the belt.

Variations in the degree of mineralisation along the belt are thought to be directly related to variations in the amount of metal provided at the ocean rise to the lithospheric plate.

Sillitoe points out that his theory of ore-genesis does not require, as others do, the existence either of long strips of upper mantle or crust, each characterised by enrichment in one or more metals, lying parallel to each other and to the continental margin. He also points out that although tin deposits of more than one age occur in

Bolvivia this does not weigh against his model as he thinks that compressive plate junctures are relatively permanent.

For a while many geologists believed that by invoking a model more-or-less the same as that proposed by Sillitoe it should be possible to account for the genesis of the overwhelming majority of tin-deposits in orogenic tin provinces. (Mitchell and Garson, (1976) recognized that the cassiterite/lepidolite pegmatites of the Phangnga area of Peninsular Thailand probably constitute an exception. These deposits are aligned along the Phangnga fault zone which is thought to be a portion of a transform fault system. It is thought that the agents responsible for the genesis of the pegmatites ascended via the fault system.)

On occasion, it was thought necessary to postulate a number of subduction zones, of distinctly different ages, or two subduction zones, active at the same time, but dipping in opposite directions, to provide adequate solutions. Such models have been proposed by Katili (1973) and Hutchison (1973) for portions of Southeast Asia. Mitchell (1973) has suggested that in some cases the development of tin deposits may be genetically related to the opening of marginal seas.

Recently it has come to be recognized by some who interpret the development of tin provinces in terms of plate tectonic models that it is probable that at least most of the tin in primary deposits is derived from the crust. Thus, Mitchell and Garson (1976, p. 153) regard the absence of tin from most island arcs which lack exposed pre-Mesozoic rocks, "provides evidence that crust of continental thickness, perhaps with a lower layer of high-grade metamorphic rocks typical of pre-Cambrian rocks on the continents, is necessary for the generation of tin-bearing magmas. This realisation of the importance of the crust as a source of metals has led Mitchell (1973) to propose a model that differs significantly from that of Sillitoe's, discussed earlier, for the generation of the parallel Andean metallogenic provinces, and which overcomes the difficulty of accounting for the fact that these provinces are of different ages. Mitchell's model, according to the account in Mitchell and Garson (1976, p. 153) "requires that mineralisation is related to a heat source at approximately constant depth, along the Benioff zone, with lateral migration of this source beneath crust of varying thickness and perhaps composition resulting from changes in inclination of the Benioff zone with time".

Further impetus to the view that during the genesis of tin provinces the tin is largely derived from crustal sources is provided by the thought that some tin provinces, such as the Hercynian ones of the Erzgebirge and the Southwest of England and the Main Range tin belt of Malaysia, were developed in continental collision magmatic belts. Thus, Mitchell and Garson (1976) are of the opinion that the tin-bearing granites of the southwest of England were developed in an underthrusting continental plate resulting from continental collision, and that the setting was similar to that of the late Tertiary Malarkachung Granite in the Himalayas. It is thought, by Mitchell, that the granites and the tin are likely, in such continental collision settings, to have been derived from the lower continental crust because it is not likely that subducting oceanic crust, which might be a possible source, is to be found beneath collision belts, and because the high $^{87}Sr/^{86}Sr$ ratios of the granites, suggest that they are of crustal origin.

That not all granites generated as a result of continental collision have tin deposits associated with them (the Himalayan example, noted above, is tin-barren) may be because tin deposits only develop from crust in which older concentrations of tin occur.

To return to the anorogenic tin deposits, noted earlier, such as occur in Rondonia and Nigeria. These deposits are associated with sodic granites in ring complexes. It is now generally thought that they have developed over hot spots before 'rifting and crustal extension which precedes the creation of oceanic crusts and the separation of continents'. Dmitriev et al (1971) have provided evidence that young oceanic igneous rocks in the vicinity of hot spots have high trace-element contents, so it is possible that some, or all, of the tin of the anorogenic deposits may be mantle-derived. On the other hand the $^{87}Sr/^{86}Sr$ ratios of the Younger Granite of Nigeria suggested that at least some of the granite may have been derived from continental crust, and so, therefore, some or all of the tin and niobium associated with these granites may well have been largely or wholly derived from the same source (Bowden and van Breemen (1972)). That the cassiterite and columbite occurring in the Younger Granite of Nigeria have been derived from the Older Granite is not accepted by all is, in part, because of the relative extent and distribution of the two granites, and because the older is tantalum- not niobium-rich.

In concluding this section one can affirm that during recent years studies of the distribution and genesis of tin provinces in the light of plate tectonics have proved remarkably fruitful and the results are most exciting. However, the fact that there are still widely differing views as to which model is the most nearly correct one for a given tin province serves to highlight the fact that we are still in the preliminary stages of the investigations. As yet insufficient account has been taken of the available data and as yet certain most important data are unavailable. Thus, for example, tin mineralisation may have occurred on at least three different occasions in Malaysia, during the Upper Carboniferous, the Triassic and the Upper Cretaceous/Lower Tertiary. If this is correct, an acceptable plate tectonic model must take account of it; but as yet we are not absolutely certain that it is correct. So there is an urgent need to date, by radiometric means, and whenever it is possible, components of the primary tin deposits. Unfortunately K-feldspar is rarely present in the Malaysia tin lodes and veins—in fact, as far as I know it only occurs in the Pelepah Kanan ones—but micas and tourmalines are present in others and these can be dated. In Cornwall, also, much more needs to be known about the ages of the mineralisation. There the problem is much easier as K-feldspar is quite a common component of the lodes and veins (Hosking, 1967) and adequate material for dating can be found on scores of mine-dumps and this can supplement that collected *in situ*. Pitchblende and other material useful for dating also occur.

TIN PATTERNS WITHIN TIN PROVINCES

In this section it is convenient to discuss the following topics and in the order given:-

A. The tin-bearing species: further considerations.

B. The classification of the tin deposits.

C. Mineralogical aspects of the patterns of primary tin deposits.

D. Relationships between tin distribution patterns and igneous rocks.

E. Tin distribution patterns in the surface and near-surface environments in tin provinces.

A. The tin-bearing species: further considerations

As noted earlier, the tin-bearing species can be classfied according to whether the tin they contain is an essential or non-essential component, and a number of rather general observations concerning the members of these two classes has already been made. At this stage it is relevant to consider the roles these species play in the various tin distribution patterns within tin provinces, and how their study may throw further light on the genesis of tin provinces and of the individual tin deposits within such provinces in a direct way, and also by prompting questions whose solution will advance our knowledge of the subject under discussion.

Many of the tin species are rare and are restricted, or virtually restricted, to one class of deposit. This is so, for example, of the tin borates and silicates whose home is in the skarn deposits and concerning whose genesis, generally, much still remains to be discovered. Malayaite, which though rare, seems to be the commonest of the tin silicates, is not confined to the Southeast Asian tin province, but in the latter it appears to be restricted to certain skarns in the western of the two major tin belts in which it has been recorded from eight or nine localities in Malaysia and Thailand. This interesting distribution pattern prompts one to ask why the species is, apparently, absent from the skarns of the east tin belt. Its distribution is but one of a number of marked differences between the two tin belts which have to be taken into account when erecting a plate tectonics model for the tin province.

Many of the tin-bearing sulphides are rare. Some, such as cylindrite and teallite are extremely rare, although in some of the Bolivian xenothermal lodes they are present in considerable quantity. Also, in the Tsumeb deposit of Southwest Africa certain tin-bearing sulphides occur which have never been recorded from other deposits. These species are "Fire Mineral" ($Cu_3(Sn, Fe, Zn, Ge)S_4$, mineral "Lu" ($Cu_2(Sn, Fe, Ge, Zn)_2S_4$, and "Maygreen" ($Cu(Ga, Sn, Zn, V)S_2$. Much still remains to be discovered about the factors that determine the genesis and distribution of the tin-bearing sulphides within individual deposits and provinces, but of recent years much has been done towards solving the numerous complex problems that such a study holds, and in this connection I cannot refrain from mentioning the most important contributions made by Moh and his colleagues at Heidelberg (Moh, 1977).

Further remarks concerning the occurrence of non-essential tin in minerals is deferred, for convenience, until later.

Whilst in a paper such as this one can reasonably dismiss most of the tin species in a summary manner, cassiterite, because of its overwhelming economic importance, demands different treatment. I do not propose to include here those properties of cassiterite which are generally well known and which, in any event, can be readily obtained from the literature. Rather I wish to present some of its variations which enable it to impart distinctive characteristics both to individual lodes and the like and to tin provinces.

Cassiterite, which crystallises in the tetragonal system, is capable of displaying a variety of habits, some of which tend to be restricted, or to reach maximum development, in certain types of deposit, and in a given deposit containing more than one generation of cassiterite the habit tends to differ from generation to generation.

Bipyramidal {111} and slightly modified squat bipyramidal cassiterite are usually found in pegmatite/aplite deposits in tantaliferous provinces and in placers derived from them. Representative material occurs, for example, in the pegmatites/aplites of Wodgina (Australia); Kamativi and Bikita (Southern Rhodesia); Ziare; Stoneham and Greenwood (Maine, U.S.A.) and Kedah Peak and Bakri (Malaysia). In pegmatites such cassiterite may be associated with cassiterite of a different habit that may have developed a little later or very much later than the bipyramidal one. It has to be appreciated that it is probable that the cassiterite within a given pegmatite/aplite body can be a product of the pegmatite/aplite magmatic fraction, and so syngenetic with respect to the body, or the cassiterite may have been deposited within the pegmatite at a later date (perhaps at a very much later date). In the latter case the cassiterite may have a habit that departs considerably from that which I think is the true pegmatite/aplite cassiterite, that is, cassiterite which possesses a bipyramidal habit or one which shows very restricted prism development and is terminated by squat pyramids.

Kostov (1968, p. 107) records that Varlamoff (1949) mentioned that in the Kalima tin deposit of what was then the Congo "bipyramidal crystals are found in the deeper levels within a granite intrusion, short prismatic crystals ....., as a rule more modified and often twinned, at intermediate levels, whereas at higher levels and away from the intrusion the crystals tend to be prismatic". Kostov continues, "the trend of crystallisation can be interpreted in terms of falling temperature and rising supersaturations. Finally, impurities (Fe, Nb, Ta) can also play a role in shortening the habit of the higher temperature types".

Bipyramidal {111} crystals, only slightly modified, may occur in deposits other than pegmatites/aplites and in provinces other than tantaliferous ones. Thus, in one of a number of veins consisting of sericite and muscovite, with very minor quartz, that occurs in schists at Rotonde (Ruanda), a crystal of cassiterite, with {111} faces well developed and the {101} faces slightly developed, and weighing ca. 50 kg, was discovered (Slatkine, 1966). These veins are in a tantaliferous province.

Collins (1882) described cassiterite from the Pell Mine, Cornwall, in which the {111} faces overshadow all the others. This cassiterite occurs in a hydrothermal vein in non-calcareous hornfels; in a province that is certainly tantalum/niobium deficient and in an area in which there are scores of other stanniferous veins, occurring in virtually the same geological environment, which lack cassiterite of a similar habit. The suggestion made by Kostov, and noted above, that iron might play a role in the development of bipyramidal cassiterite, and cassiterite of closely allied habit, is surely not the reason for the habit of the Pell Mine cassiterite, as there was an ample supply of iron during the deposition of most of the Cornish cassiterite (judging by its colour). So, what determined the habit of the Pell cassiterite is unknown.

In greisen-bordered veins and other similar early stanniferous bodies that usually post-date any stanniferous pegmatites in their neighbourhood, one commonly encounters cassiterite crystals consisting, essentially, of short prisms and {111} pyramids. These are the dominant type in, for example, the greisen-bordered veins of St. Michael's Mount and of Cligga (Cornwall) and in those of Gambang (Pahang).

Cassiterite developing later in the sequence and occurring, for example, in the chlorite-rich lodes of Cornwall, tends to have long prisms and acute and complex pyramidal terminations. At South Crofty Mine (Cornwall) a further and very rare variation occurred. There, locally lining druses, was found, about 15 years ago, cassiterite crystals, up to 2.5 cm in length, that consisted of barely developed prisms doubly-terminated by acute pyramids.

On occasion, a late generation of cassiterite may be of the acicular type. This is well seen, for example, in the stanniferous skarns of Thailand, where it is associated with an earlier generation of massive cassiterite, and in the wood-tin-bearing lodes of the St. Agnes area of Cornwall. In the latter case the wood-tin consists of radiating acicular crystals which are generally believed to have crystallised from a gel, whereas other primary acicular crystals associated with the wood-tin, and which may be earlier and/or later than the wood-tin, appear to have been the product of direct crystallisation from hypogene agents either in an open space or by replacement.

It is pertinent to remark that acicular cassiterite, together with chalcopyrite, may develop by the decomposition of stannite (Ramdohr, 1950, and Santokh Singh and Bean, 1968, pp. 462–464) by hypogene processes whilst, as noted earlier, Edwards and Baker (op. cit.) provide evidence that, on occasion, acicular cassiterite may also develop when cassiterite is attacked by supergene agents.

It seems that rather special physico-chemical conditions are necessary for the development of wood-tin: were this not so one might expect to find it in more than the one locality in Malaysia (Smith and Hosking, 1974) and, indeed, in many other localities in Southeast Asia, yet it has only been reported from one other, namely at Huai Tagrao in Phanom Sarakham district, Chachoeng Sao Province in Peninsular Thailand (Aranyakanon, 1970). Wood-tin is, I believe, absent from the tin deposits of South Africa and but few occurrences are known in Australia (personal communication, R.G. Taylor). Certainly this particular variety of cassiterite is rather rare and reaches its most marked development in some of the Bolivian and Russian xenothermal deposits and in those which are associated with volcanics in Mexico and in similar fumarolic deposits of the south-west U.S.A. and Argentina. The evidence suggests that wood-tin was deposited initially as a gel at modest depths, and possibly at modest temperatures, although the fact that at West Wheal Kitty (St. Agnes, Cornwall) the wood-tin, having been fractured, is locally veined and replaced by iron-rich sphalerite containing exsolved bodies of chalcopyrite, suggests that the temperature may not have been particularly low. That wood-tin has generally developed from stannite by supergene processes has been proposed (Jones, 1925, pp. 40–41) but I do not think this is so, although varlamoffite after stannite, on occasion, shows a crude, possibly colloform, banding.

Wood-tin is associated with effusives and/or high-level intrusives, and although most occurrences are associated with orogenic deposits, wood-tin also occurs in some of the anorogenic deposits of Nigeria and Brazil.

As noted above, wood-tin is not always the latest of the hypogene cassiterites to develop: it may be followed by acicular cassiterite, and at Wheal Enys (Cornwall) voids between the masses of wood-tin, and fractures within it, are locally in-filled with a mosaic of pale cassiterite that is reminiscent in habit of early cassiterite. This latest member, in addition, part-replaces the wood-tin.

It is necessary to boldly state what has been briefly noted above, that is, that it is not uncommon for a hard-rock tin deposit to contain more than one generation of cassiterite, and each generation may be recognized by its particular habit, together with other characteristic features such as colour, the nature of its colour zones (if any are present), and its pleochroism (if such is displayed). Thus one finds, for example, in the one of the veins of Hin Fatt No. 2 mine (near Kuala Lumpur, Selangor) massive, brecciated, appreciably pleochroic, cassiterite part-bordered by a palisade of later acicular cassiterite crystals which are virtually non-pleochroic.

As noted above, Kostov (1968, p. 108) ascribes changes in the habit of cassiterite in the Kalima tin deposit to falling temperature and rising supersaturation with time. Possibly a reverse trend in the habit, such as happened in the Wheal Enys deposit, that is referred to earlier, may be due to diminished saturation. Kostov has postulated this to account for certain variations he has observed in the habit of quartz, so it might equally well apply to cassiterite. On the other hand, it may be that variations in the trace-element content of the agents from which the cassiterite was deposited may have played a role, perhaps a dominant one, in determining the habit of the tin mineral.

Cassiterite crystals may vary greatly in size from one type of ore deposit to another and within a given ore deposit. Generally speaking large crystals are most commonly found in pegmatite/aplite deposits although, as noted earlier, cassiterite crystals from greisen deposits may, on rare occasions match, in size, any from pegmatite/aplite deposits. The later, structurally and mineralogically more complex lodes, and the stanniferous skarns, tend to be characterised by the fact that most, if not all of the cassiterite present, is in the form of rather small crystals, although their centres of crystallisation were sometimes so close that the growing crystals suffered mutual interference and hence large masses of cassiterite may be seen in such ore bodies. It is in the complex lodes, also, that one commonly meets with great variation in the size of the cassiterite crystals. Thus, in the Cornish lodes, for example, some of the cassiterite crystals may be a cm or more length, and in the same bodies cassiterite crystals of only one or two μm may also be present. Davison (1919, pp. 279–281) records such small crystals disseminated in zones within quartz crystals from the South Crofty lodes. The long-abandoned Wheal Primrose (St. Agnes, Cornwall) provided ore characterised by the presence of exceedingly small crystals of cassiterite (1–2 μm in length). This ochre-coloured ore, consisting essentially of minute cassiterite crystals in a quartz matrix, which was locally replaced by coarser cassiterite associated with chlorite, was somewhat drusy. The druses were lined with quartz crystals that were ochre-coloured because of the disseminated cassiterite they contained, and when they were discovered during the last century they were thought to be crystals of a tin silicate.

It is relevant to mention again here that minute cassiterite crystals may occur on cleavage planes of white micas in stanniferous provinces and that in such provinces exsolved cassiterite may be encountered in magnetite, wolframite, and columbite/tantalite.

Generally speaking, the most spectacular museum specimens of crystalline cassiterite come from those deposits which, from an economic point of view, are not particularly attractive to the hard-rock miner, that is, from the pegmatites/aplites and greisen bodies. There are, of course, exceptions to the latter part of this observation, and these are those bodies, which although possessing a modest grade, are, by virtue of their size, capable of being mined on a large tonnage basis: such are the pegmatites of Monolo, Zaire, and of Kamativi, Rhodesia.

Cassiterite may occur in a wide variety of colours. On rare occasions it is pink, as in certain greisen deposits of Thailand; red (Nigeria); Chartreuse green (Uganda); and golden-yellow (Peninsular Thailand). Colourless, transparent crystals, several cm in length, occur in Uganda, and similar crystals, but much smaller, are occasionally encountered amongst the Malaysian and Nigerian placers. In Cornwall, at South

Crofty Mine and at Wheal Reeth, the outermost rims of brownish cassiterite crystals are also sometimes colourless and transparent, a fact only established by examining the material in thin section under the microscope. At Ayer Hitam (Selangor) milk-white, grey and near black cassiterite crystals are not uncommon in the concentrates from the dredges. Generally, however, cassiterite is brownish in the hand-specimen and often, in thin-section, crystals of the mineral display colour-zoning. Usually the coloured bands vary from near black through browns, orange, pale-ochre to colourless, and there is a common tendency for the deepest coloured zones to congregate at or near the core of the crystal. Sometimes within a given mine the cassiterite from each lode is, by virtue of its colour zoning, sufficiently characteristic in thin section for it to be used to correlate portions of lodes that are separated by a block of virgin ground. I was able to do this 15 or 20 years ago at South Crofty Mine (Cornwall). In other mines, for example, Pahang Consolidated Mine (Malaysia) such marked difference is not to be found.

TABLE 2

PLEOCHROISM OF MALAYSIAN CASSITERITES
(AFTER SCRIVENOR, 1928)

Extraordinary Ray	Ordinary Ray
1. Carmine	Olive green
2. Carmine	Pale sepia
3. Pale carmine	Colourless
4. Orange-brown	Brown
5. Dark-brown	Light brown
6. Mauve	Colourless
7. Yellow	Light yellow

When the cassiterite crystal contains an appreciable quantity of tantalum (or Nb?) in the lattice it may display some interesting pleochroic effects, and at its most spectacular, on rotating the microscopes stage, and with the polariser inserted, the crystal may change from some very pale shade to blood-red. Table 2 provides details of the variations in the pleochroism of Malaysian cassiterites that were recorded by Scrivenor (1928, p. 28).

I have established (Hosking, 1977) that from the point of view of pleochroism there are some interesting and marked differences between the cassiterites of the West and East Belts of the Southeast Asian Tin Province (Fig. 2). The variations, noted by Scrivenor, and mentioned above, are all to be found in the West Belt, but, of considerable importance is the fact that in many localities there are cassiterites whose pleochroism is, what I term, of the pale-colour/blood-red variety. With very few exceptions the cassiterites of the East Belt to not display strong pleochroism and none that I have examined are characterised by displaying the intense pale-colour/blood-red pleochroism. The most intense 'red pleochroism' is provided by the cassiterites from the pegmatites and early greisen-bordered veins whereas the cassiterites from the later hydrothermal lodes may show a 'faint red' (or pink) pleochroism, although usually the

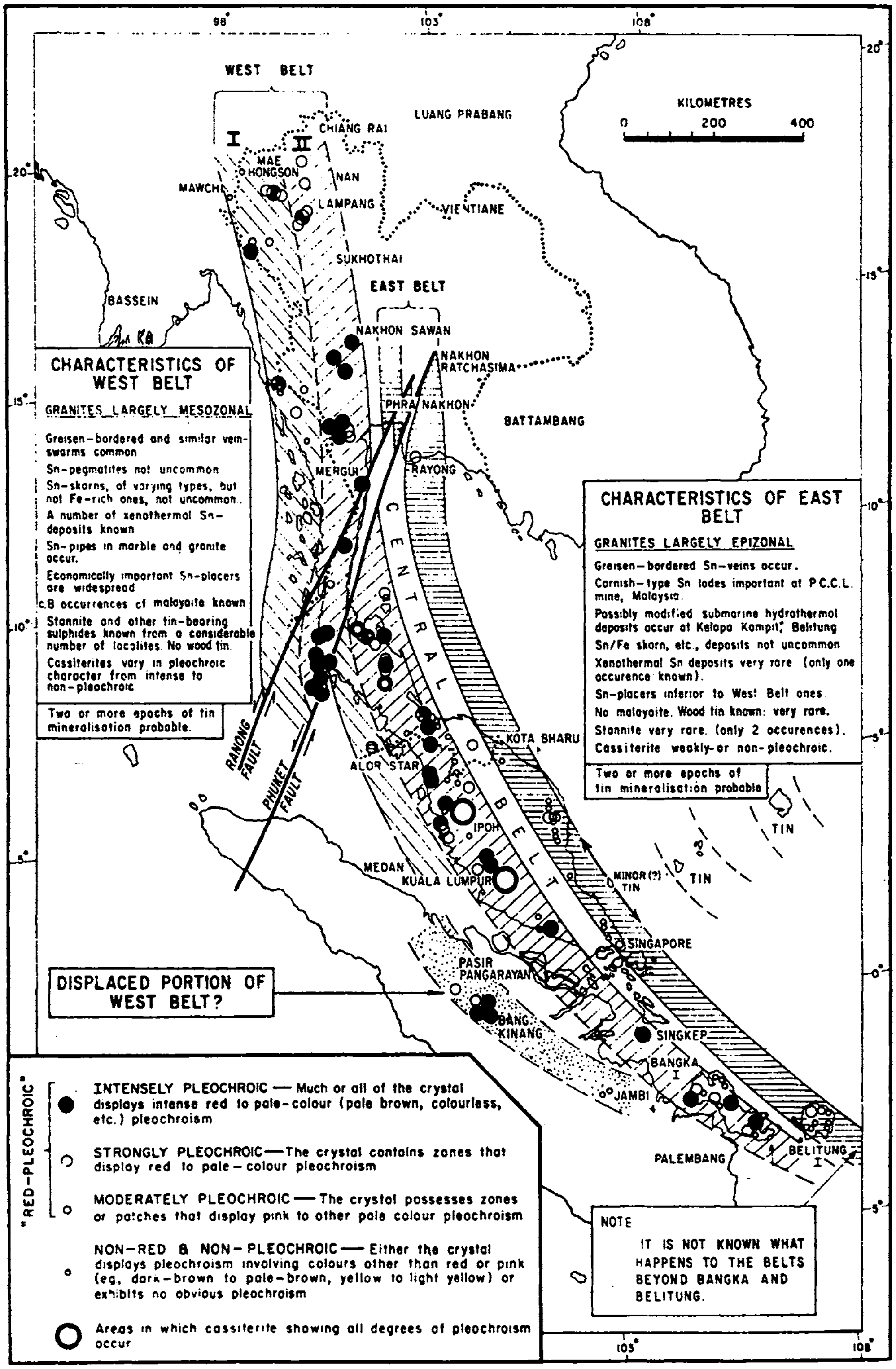


Fig. 2. Tin Belts of Southeast Asia and the pleochroic character of the cassiterites within them (After Hosking, 1977).

pleochroism is of the brown variety. (In one thin section of tin-ore from Kelapa Kampit (Belitung), out of the scores that I have examined, there was cassiterite that displayed a strong mauve/colourless pleochroism). If the red pleochroism is due to tantalum in the lattice, then one might expect the intensity of the red to decrease as one passed from true pegmatite cassiterite, to that from somewhat later greisen-bordered veins and thence to the later hydrothermal lodes. However, the pleochroism of the cassiterite from greisen-bordered veins from the East Belt never matches in intensity that of the cassiterite from some of the similar bodies of the West Belt. These facts, together with a number of other marked differences in the mineralisation of the two Belts, which I have noted elsewhere (Hosking, 1977) and the probability that each Belt contains tin deposits of at least two different ages, and perhaps more, suggest to me the possibility that each Belt may have had its own crustal source of tin, and that each source was tapped on two or more occasions. The same may be said for some of the other ore minerals found in the Belts (Hosking, 1977). It is also clear that a satisfactory plate tectonics model for the Southeast Asian Tin Province must account for these differences.

To return to the pleochroism of cassiterite. In the West Belt of the Southeast Asian Tin Province it is not uncommon to find cassiterite with intensely red pleochroic bands separated by pale bands that are weakly pleochroic or non-pleochroic and, on occasion, these bands are cut across by brown bands which may show a 'brown pleochroism'. The latter bands probably owe their colour to iron, as Leube and Stumpfl (1963) have demonstrated that in a specimen of brown-banded cassiterite, which they examined by means of the electron probe, the intensity of the brown colour varied with the iron content. The developemtn of the red and brown-banded cassiterite provides interesting but unresolved problems. Doubtless, colour bands that parallel observed crystal faces are due to fluctuations in the composition of the mineralising agent, whilst the other colour bands may parallel other possible crystal faces. Irregular colour patches with diffuse edges, which are not uncommon in cassiterite crystals, may reflect compositional variations in a host that the cassiterite partly, or wholly replaced. Furthermore, in some of the early cassiterites one finds exsolved bodies of columbite/tantalite or mossite/tapiolite and these may be haloed by cassiterite that displays strong red pleochroism. Such cassiterite occurs, for example, in the deposits of the Chenderong Mine, Trengganu (Malaysia). A detailed study of certain red-pleochroic Malaysian cassiterites has been made by Santokh Singh and Bean (1968, pp. 469–471). The spectacular red pleochroism of cassiterite is restricted to tin/tantalum/niobium provinces, and in those which are Ta(Nb) impoverished the pleochroism is virtually restricted to the brown type and is generally weak as, for example, in Cornwall. There, some of the cassiterite from the St. Agnes lodes, which are in non-calcareous hornfels, displays a faint pink to colourless pleochroism. This is on of the few bits of visual evidence for the probable presence of tantalum in some Cornish cassiterites that I have seen.

During the smelting of the Southeast Asian cassiterite concentrates tantalum accumulates in the slag and the latter has been used as a source of tantalum. However, it is probably that most of the tantalum derived from the cassiterite concentrates is from exsolved Ta/Nb species and not from the tantalum in the cassiterite lattice.

Cassiterite may be magnetic, but whereas in some tin provinces magnetic cassiterite may be quite abundant (several percent of all the cassiterite recovered from Southeast Asia, is magnetic) in other provinces, as in that of the Southwest of England, it is extremely rare. In the latter province a grain or so, no more, of magnetic cassiterite have been recovered in the past, but only from concentrates from Cligga and Wheal Reath (R.B. Michell, personal communication.) In addition, some grains of cassiterite from South Crofty are magnetic due to inclusions of wolframite that were captured at those places where the tin-bearing lodes intersect wolframite-bearing ones, and further grains of cassiterite from Wheal Prosper display the same property because of relict magnetite collected during the development of the cassiterite by metasomatic processes.

Both ferromagnetic and paramagnetic cassiterite are known, and both occur, for example, in Malaysia. In Malaysia the ferromagnetic type, whose magnetic property is destroyed by heating to 830 °C for 15 minutes (Flinter, 1960), occurs in areas in which the cassiterite is in close association with iron ore, as at Pelepah Kanan, Johore. Studies of Pelepah Kanan cassiterite by Grubb and Hannaford (1966) have demonstrated the darker the colour zone, the greater its magnetic susceptibility. This was subsequently confirmed by Khoo (1969).

Grubb and Hannaford conclude that the magnetization appears to be associated with the presence of hydrated ferrous stannate and that these inclusions are probably accompanied by some local dehdrated regions containing ilmente-type $FeSnO_3$. This anhydrous ferrous stannate might then be expected to be found in solid solution with any trace of hematite which may have been present—possibly as a result of dehydration of α-FeOOH or γ-FeOOH and form a series of rhombohedral compounds (analogous to Fe_2-xTi_xO_3) which, at the appropriate concentrations, should exhibit appreciable ferromagnetism.

In Malaysia paramagnetic cassiterite, whose magnetic property is not destroyed by heating, occurs in association with columbite-tantalite and related species, and is found at Bakri, Johore and at Kedah Peak, Kedah. Bradford (1961) suggests that the magnetic character of such cassiterite may be attributable to the presence of tapiolite in solid solution. In contrast, in Nigeria, the magnetic cassiterite which is recovered from placers, etc., with columbite, is ferromagnetic. This black cassiterite, on heating in an open crucible for c. 10 minutes at c. 1000 °C., loses its magnetic property and on cooling it is found to be, and to remain, permanently red. This red cassiterite will not react positively to the 'tinning test'. Many dark cassiterites that I have heated under the same conditions as those applied to the Nigerian cassiterite, and noted above, become reddish on cooling and even the white cassiterite from Ayer Hitam, Selangor, assumes a colour similar to that of rose quartz, when so treated. Such treated cassiterites are slow to tin, or may not tin at all when subject to the tinning test. It also seems reasonable to think that some naturally-occurring red cassiterites, such as have been recovered, for example, from the Nigerian placers and Mexico, may owe their colour to heating by volcanics. In addition, forest fires and the like might be responsible for some of the red cassiterite that is encountered, on occasion, in superficial deposits.

Before leaving the question of cassiterite colour it is pertinent to remark (Hosking, 1973, p. 366) that I found certain crystals in lode material from the western margin of the Kinta Valley, from the Puchong area, near Kuala Lumpur, and from the Beralt Tin and Wolfram Mine, Portugal, fluoresced a dull but distinctive orange under shortwave ultraviolet light. I think that this might be due to the presence of a thin veneer of a colourless, transparent mineral, possible apatite, perhaps activated by a trace of manganese.

From what has been already written it is clear that the tantalum content of cassiterite is subject to wide variation and that in Malaysia the content of this element tends to decrease from pegmatite cassiterite, via that from the greisen-bordered veins to the later hydrothermal deposits such as the cassiterite/sulphide lodes of Pahang Consolidated Mine. Earlier Dudykina (1959)(as recorded by Leube and Stumpfl, 1963) had established a similar trend amongst cassiterites from the U.S.S.R. Dudykina's work also showed that niobium, scandium and titanium behaved in the same way as tantalum, whereas lead, silver, arsenic and antimony behaved in a manner that was antipathetic to that of tantalum. These results, in part tabulated below, suggest that concentrations of certain trace elements (not all, not, for example, that of beryllium) are determined to some considerable degree by the physico-chemical environment in which the cassiterite was developing. Within an area of limited extent the decline in the concentration of tantalum, and those other elements that behave in a manner similar to that of tantalum in cassiterites as one possesses from pegmatites, via greisen-bordered and similar types of deposit, to the later tin/sulphide bodies, probably reflects a corresponding decline in the temperature of deposition. It is also likely that this same trend generally reflects a decreasing depth of deposition. Thus, commonly stanniferous pegmatites are deposited at greater depths than the greisen-bordered and similar stanniferous veins and these, in turn, are developed at greater depths below the surface than the tin/sulphide lodes, but I am sure that this is not always the case. Nikulin's (1967) work on the cassiterites of the Khingan deposit of Eastern Siberia supports the view that there is a change in the trace element pattern of cassiterites with depth. This worker demonstrated that whilst the niobium and scandium content increased with depth, that of indium decreased. The overall picture noted above is further broadly confirmed by Stevenson and Taylor (1973) who investigated the concentrations of certain trace elements in 43 specimens of cassiterite, from a variety of different types of deposit in Eastern Australia. They found in the samples they studied that "Nb and Zr contents are highest in the pegmatite and greisen types, and lowest in the quartz-sulphide types. Ta also reaches highest concentrations in the pegmatite and greisen types and is below detection limit in the other environments. Sc is detectable in

TABLE 3.
TRACE-ELEMENT CONTENT OF CASSITERITES FROM VARIOUS TYPES OF DEPOSIT IN THE U.S.S.R. (AFTER DUDYKINA, 1959)

	No. of samples analyzed	Nb.	Ta.	Sc.	Be.	Ti
		(in ppm)				
I. Tin-bearing pegmatites	37	6,000	5,300	650	10	4,100
II. Quartz-cassiterite (a) Greisens and quartz-feldspar veins with topaz, tourmaline and beryl	38	5,200	15,570	580	20	7,500
(b) Quartz veins	129	600	150	400	10	3,500
(c) Transitional deposits	24	30	—	140	50	4,000
III. Sulphide-cassiterite deposits	43	20	—	4	10	1,700

cassiterite from all the types of cassiterite deposit investigated, and apart from being almost absent in the pegmatitic groups, shows no clear genetic associations. Indium is similarly low in the pegmatite group, appears to be generally high in the greisens, and shows no clear genetic association in the remaining groups. In two environmental types sulphide-rich members contain significantly low In contents". Although, as noted above, the above results *broadly* confirm those of others, there are distinct differences.

Sc, particularly, displays a distinctly different behaviour in the deposits investigated by Dudykina when compared with those with which Stevenson and Taylor were concerned. So one can reasonably conclude that the trace element content of cassiterite is not simply a function of the depth nor of the temperature at which it developed. It is at least possible that, in part, it reflects variations in the trace-element content of the source of the ore-forming agents and/or variations in the trace-element content of the rocks through which the ore-developing agents moved during their ascent ot the sites of cassiterite deposition. To conclude this section, and lest it should be forgotten that this paper is concerned with tin distribution patterns, it is pertinent to record here how the varying properties of cassiterite might be employed to reveal distribution patterns that on analysis might throw further light on the whole question of the genesis of tin deposits.

It has already been noted that the distribution of cassiterite according to its degree of pleochroism prompt questions re the evolution of the tin province of Southeast Asia. This variation in pleochroism is thought to be due to variation in the tantalum and possibly niobium content in the cassiterite lattice, and so similar plots of other trace elements occurring in cassiterite in the tin province in question, and in others, might provide patterns that suggest further questions of genesis. Similar reasons might be advanced for plotting the distribution of ferromagnetic and paramagnetic cassiterite. In such regional studies it is obvious that the material studied should, ideally, be from *in situ* hard-rock deposits, although cassiterite taken from the uppermost reaches of tributary streams is also worth investigating.

Within hard-rock mines it has been noted that the colour zoning of cassiterite may, on occasion, facilitate the correlation of portions of lodes separated by bodies of unworked ground. In addition, there is also evidence that the trace elements content of cassiterite tends to change with depth. Possibly, therefore, the plotting of the concentrations of selected trace elements in cassiterite samples taken from a lode that has been exposed for considerable distances along its strike and dip by mining might provide useful clues as to how the ore body in question had developed. It is commonly believed that the cassiterites in the deepest parts of a lode were deposited before those in the shallower horizons, but this may not always be so, and trace element studies of the type just mentioned may point to the truth, and in any case supplement those data obtained by determining the temperatures of formation of the cassiterite and associated species.

B. The classification of the tin deposits

The expression 'tin deposits' is used here to cover all those naturally occurring bodies from which tin may be profitably recovered now, or in the foreseeable future. In some of these deposits, as, for example, the Sullivan ore body of British Columbia, the tin, occurring as cassiterite, is recovered as a by-product.

As the character of the tin distribution pattern of a given province is largely dependent on the nature and distribution of the various types of primary and secondary tin deposits it contains, and on the spatial and temporal relationships between these deposits and the intrusives and effusives of granitoid composition within the province, it is necessary, at the outset, to consider how the tin deposits should be classified.

At the outset one can say that data are not available to erect a satisfactory genetic classification of tin deposits, and were a genetic classification produced now that was widely accepted it would probably serve as a deterrent to advancement in the understanding of the genesis of the deposits in question and to the search for such deposits.

Gilmour (1962) when proposing a non-genetic classification of copper deposits provided the following comments, with which I am largely in agreement and which, in may view are equally relevant to the question of the classification of tin deposits:- "In English-speaking countries, at least, the systems of classification most widely used for copper and other mineral deposits are based on the supposed mode of origin of the deposits (footnote). Instead of recognizing the genetic basis as a defect some authors appear to consider it in asset ...., yet in our present state of knowledge of the origin of ore deposits the application of a classification based on mode or origin must be subjective and arbitrary. A genetic classification is comparable, say, to a zoological classification derived from some worker's notion of phylogeny rather than from observed anatomical features. Obviously, a classification of ore deposits should be made as objective and as descriptive as possible and with this object descriptive criteria, such as the form and composition of the deposits and the type and setting of the host rocks, should be employed". Towards the end of his paper Gilmuir expresses the further view that "one of the principal reasons for making any classification as objective as possible is that the classification may stand no matter what happens to theories of origin".

Unlike Taylor (1974a, p. 79) I am not of the view that there is no satisfactory classification of tin deposits. A classification is a satisfactory one if it effectively serves the purpose for which it was erected. Thus, for example, the classification of tin deposits according to their economic importance, which was adopted by Schuiling, and which was referred to earlier, was perfectly adequate for his purpose. By the same token I think that my classification of the primary tin deposits of Malaysia was satisfactory for the purpose for which it was used (Hosking, 1974, pp. 42–43). It is only when one is considering the classification of **all the known types of tin deposits of the world from the point of view of those who are concerned with the problems of ore-genesis** that Taylor's opinion is in accord with my own. Obviously the problem of constructing a generally satisfactory classification of these deposits lies in the prevailing differences of opinion concerning which criteria should be used as the basis of the classification, and the order of priority which should be adopted for the criteria chosen. The criteria which have been adopted in published classifications include the temperature of deposition, the mineralogical character of the deposit, the geological environment in which the deposit developed and the morphological character of the deposit. For the purpose of this paper I have elected to adopt the following basic classification of tin deposits of economic interest which does not differ greatly either from the one I proposed a few years ago (Hosking, 1974, p. 41) nor from that of Mulligan (1974, pp. 44–45):-

1. Disseminations other than those in modern placers and definite fossil placers and that are not included in the other major groups.

As far as tin deposits are concerned this statement is no longer true.

2. Pegmatites/aplites.
3. Skarns ("pyrometasomatic deposits").
4. Deposits associated with greisenised country rock.
5. Stanniferous veins other than those of the greisen-associated type.
6. Lodes of the Cornish type.
7. Replacement ("metasomatic") deposits, of modest dimensions, that cannot be satisfactorily placed in any of the other groups.
8. Telescoped, mineralogically complex deposits ("xenothermal" or "subvolcanic" deposits).
9. Deposits of the Mexican type (i.e., epithermal or fumarole deposits).
10. Stanniferous massive sulphide and massive iron oxide deposits.
11. "Ancient", variously modified, stanniferous sedimentary deposits.
12. "Modern" placers.

[The genetic terms (e.g., "pyrometasomatic", "xenothermal") that have been placed in brackets in the above classification have been included simply because for so many they still help to conjure up pictures of the deposits.]

Obviously each of the twelve groups in the basic classification can be further sub-divided and no two people will probably agree as to how best to do this. When preparing a classification of the tin deposits of a particular province which has been much investigated and with which one is very familar, the further sub-division does not offer an excess of problems, in part because one is likely to know just about all the types of tin deposit occurring there, and because it will not contain all the known types of tin deposit. Clearly, at province level and below, a **detailed** classification, that is reliable, has much to recommend it as it can form the foundation of studies involving the development of a variety of distribution maps, as, for example, ones showing the different types of tin deposit, the distribution of cassiterite according to its degree of pleochroism and magnetic character, the deposits in which cassiterite is associated with selected minerals such as wolframite, molybdenite, the tin-bearing sulphides and malayaite. These maps facilitate researches concerning the genesis of the tin deposits and, in addition, they may constitute a valuable aid to the prospector.

To return to the basic classification proposed above it seems relevant to provide, in an abbreviated form, **some** suggestions as to how the twelve groups may be sub-divided.

1. *Disseminations other than those in modern placers and definite fossil placers and that are not included in the other major groups.*

(i) Syngenetic with respect to the host rock.

(a) Cassiterite in granitoids.

Problem:- Difficult to establish whether some, all, or none of the cassiterite **is** syngenetic.

(ii) Cassiterite in metasediments.

Problem:- It is possible that some, or all, of the cassiterite in the metasedimentary bed adjacent to the granite may have been an original component of the sedimentary body. This is difficult to establish.

2. *Pegmatites/aplites*
   (i) Zoned pegmatites.
   (ii) Unzoned pegmatites.
   (iii) Pegmatite/aplite bodies.
   (iv) Aplite bodies.

Note:- Each sub-group can be further divided according to whether the cassiterite is wholly, in part, or not syngenetic with respect to the host.

Further sub-divisions could be made depending on minerals associated with the cassiterite.

3. *Skarns*
   (i) Stratabound skarns.
   (ii) Contact skarns.
   (iii) Vein skarns.
   (iv) Irregularly shaped skarns.

Note:- Each sub-group might be further divided on mineralogical grounds, and it might be advantageous to use as a basis the presence of tin species (particularly malayaite, on account of its possible future economic importance) other than, or in addition to, cassiterite.

The skarns may also be initially sub-divided according to the chemical/mineralogical nature of their parents (e.g., limestone, magnesian limestone, dolomitic limestone, dolomite, dolerite).

4. *Deposits associated with greisenised country rocks*

These deposits characteristically occupy the cusps (cupolae) of granitoid masses: to a lesser extent they occur in the minor intrusives, (e.g., pegmatites and porphyry dykes associated with such high-spots). These facts can form the basis of a sub-division.

The morphology of the mineralised greisenised masses is subject to considerable variation, as the diagrams of Rundkvist (1971), which have been reproduced by Varlamoff (1975), beautifully demonstrate. Such morphological variations may be used to erect further sub-divisions.

The mineralogical character of the greisen also allows further sub-division. In Cornwall, for example, the following types of greisen occur, in part as a result of the addition of species after the phase of sericitisation (Hosking, 1970a), p. 1174:- tourmaline type (Carn Brea); chlorite type (Priest's Cove, Cape Cornwall); hematite type (Cameron Quarry, St Agnes); zinnwaldite type (Greatwork Mine); fluorite type (Parcan-chy); topaz type (St. Michael's Mount and Bunny Mine, St. Austell) (topaz-fels, Belowda Beacon) and types with ore minerals (molybdenite at Cligga and Kit Hill, cassiterite and wolframite at Parc-an-chy). In other provinces greisen may be modified by the addition of albite, and indeed all gradations between greisen and albitite may exist (Varlamoff, 1975), and by a score of other species other than those found in sufficient abundance in one or more of the Cornish greisens to give the the members in which they occur a distinct character.

Further sub-divisions may be effected by considering the morphology of the cassiterite-bearing deposits enclosed by, or intersecting, greisenised 'granite'. Are they veins or pipes? If veins, do they show any curious features such as those at Cligga (Cornwall) which parallel the original granite contact and have been described as 'pseudo-bedded'?

Finally, the mineralogical character of any greisen-enclosed bodies may allow further sub-division. Do they, for example, contain appreciable wolframite in addition to cassiterite (as at Cligga, Cornwall)? Do they contain, in addition to cassiterite, wolframite and scheelite, as at Ulu Langat (Selangor, Malaysia)?

5. *Stanniferous veins other than those of the greisen-associated type*

On occasion one encounters isolated stanniferous veins that are not associated with greisen and are simply of academic interest. On the other hand one also finds swarms of such veins, perhaps with a more-or-less parallel strike, or perhaps displaying the real character of a stockwork. Such swarms are usually encountered in the country rock overlying a buried granitoid cusp. The vein content is usually much the same as that found in greisen-bordered veins within the granite. The veins often possess a selvedge of sericite or gilbertite, and the wall-rock, if it is a non-calcareous metasediment, may be locally altered to a banded quartz/tourmaline rock or to one in which sericite is present in addition to the quartz and tourmaline. Typical examples of veins with the latter type of alteration occur at West Wheal Fortune (Breage, Cornwall). On other occasions the wallrock may be altered to quartz/chlorite as it is in the vicinity of stanniferous veins at Trevaunance Cove, St Agnes, whilst at Tebu (Belitung) inert siliceous sandstone shows no obvious signs of hypogene alteration adjacent to the cassiterite/quartz veins for which it is a host.

Deposits composed of such veins may be sub-divided according to the texture and mineralogy of the veins, and the nature of the wallrock alteration (if any).

6. *Lodes of the Cornish type*

These structurally and often mineralogically complex bodies, which usually possess considerable dip- and strike-extent, may occur in a wide variety of host rocks, and individual members may persist across more than one host, as, for example, the Dolcoath Main Lode (Cornwall) does: it is present both in the granite and the granite/invaded country rock. Furthermore, they may display primary zoning as, for example, do many lodes in the Camborne-Redruth area of Cornwall, or they may not, as is the case of those of the Pahang Consolidated Mine, Malaysia.

Such deposits, then, can be sub-divided according to their textural and mineralogical characters, as to whether they do or do not display primary zoning, on the character of their host rocks and on the nature of their wallrock alteration. It is obvious that when all the possibilities are considered the possible sub-divisions of this group is a frighteningly large number even when a province such as that of the South-west of England is considered: how much greater would it be were all the deposits of the world that fall into this group so treated!

7. *Replacement ("metasomatic") deposits, of modest dimensions, that cannot be satisfactorily placed in any of the other groups.*

Falling into this group are replacements such as carbonas, floors and pipes in granitoids, examples of which are to be found in West Cornwall. Pipes also occur in the granitoids of Haad-som-pan (Thailand), the eastern granitoids of Australia and at Potgeitersous (S. Africa). Also in this group one can place some of the pipes of the Kinta Valley, which are found in marble, and which do not qualify for a place in either the skarn group or the xenothermal one. So this group can be sub-divided according to the nature of the host rock of the deposit, the morphology of the deposit, and its mineralogical character.

8. *Telescoped, mineralogically complex deposits ("xenothermal" or "subvolcanic" deposits)*

Fundamentally the members of this group can be sub-divided according to whether they are, or are not obviously closely spatially associated with volcanics. Those associated with volcanics can be sub-divided according to whether they are, or are not porphyry type deposits, or are, or are not, accompanied by porphyry tin deposits. Of course, further sub-divisions might also be made that depend on the mineralogical character of the deposits.

Both in Malaysia and Cornwall xenothermal deposits occur which are not apparently related to volcanics. Perhaps two of the best Malaysian examples are the deposits at Tekka (Perak) and the Manson Lode (Kelantan). The most spectacular xenothermal ores known to me from Cornwall were obtained from Wheal Baddern (a little to the east of the presently operating Janes Mines) and from Penberthy Croft. Both in Malaysia and in Cornwall there are a number of areas, other than those mentioned above, in which xenothermal deposits occur. It is also relevant to note that some skarn deposits, such as the Beatrice Pipe (Perak) and the Kampong Pandan bodies (Selangor) may be fairly placed in the xenothermal group. In addition, a case might be made for placing the lodes of Pahang Consolidated Mine in the group as they are telescoped in as much as they show no marked mineralogical change from below the bottom of the zone of oxidation to the deepest sites of mining and they contain a considerable variety of minerals. However, on balance, I prefer to classify the Pahang Consolidated Mine lodes and the somewhat similar lodes of Kelapa Kampit (Belitung), but not the bedding-plane veins of the latter, with the 'normal' Cornish lodes in Group 6. The genesis of the bedding plane veins of Kelapa Kampit has not been entirely satisfactorily resolved but I am inclined to Adam's view (1960) that mineralogically, at least, they can be reasonably described as skarns.

9. *Deposits of the Mexican type ("epithermal" or "fumarole" deposits)*

Deposits of this type, from a number of different localities, Southwest U.S.A., Mexico, Bolivia and Argentina, are so similar that the group cannot be reasonably further sub-divided. They consist of veinlets composed of cassiterite (some of which is of the wood-tin variety), specularite, chalcedony, cristobalite and tridymite, in generally kaolinised host-rock.

10. *Massive sulphide and massive iron oxide deposits*

This group has been introduced primarily to accommodate those tin-bearing bodies that are stratabound and consist of sulphides with interbands consisting of detrital grains of gangue minerals. "Many are underlain by or grade stratigraphically downwards into zones of lower grade pyritic or pyrrhotite-bearing "disseminated" or "vein" ore that is obviously not "stratabound" (Mulligan, 1975, p. 50). Such deposits, which are well represented in Canada, are often considerably deformed and metamorphosed.

As Mulligan (1975, p. 50) points out, this group may be sub-divided into volcanic-stratabound and sedimentary-stratabound. Deposits of the volcanic sub-group are generally "associated with rhyolitic or other alkali-siliceous rocks interbedded with more basic volcanic rocks, and thought to mark the end stage of basic-intermediate-acid volcanic cycles". In Canada many of these deposits, such as those of Kidd Creek and South Bay are near margins of sedimentary depositional basins, and the sedimentary-stratabound deposits like Manitouwadge (but not Sullivan) are commonly in sedimentary depositional basins surrounded by volcanic rocks". (Mulligan, 1975, p. 50). Mulligan also notes that in the Canadian sedimentary-stratabound assemblages iron-formation is often represented and is much in evidence at Manitouwadge. He also notes that some sulphide deposits of the type under review grade laterally into iron-formation and he suggests that the iron oxide deposits may be the shallower water equivalents of the massive sulphides. The iron-formation deposits, in addition to the massive sulphide ones, may be stanniferous. That of Grangesberg is a case in point. In the Eastern Tin Belt of Southeast Asia (see Hosking, 1977) particularly in Pahang and Belitung, there are a number of concordant and distinctly stanniferous iron oxide deposits, and some of these pass laterally, or in depth, into bodies which are essentially sulphidic: of these, a good example is the Selumar deposit of Belitung which has been locally exploited because of its cassiterite content. However, it is necessary to state that the geneses of these iron/tin deposits of Southeast Asia are still matters of uncertainty, and it is at least probable that from a point of view of genesis, a number of different types exist. It is uncertain at this stage if any of them are strictly comparable to the Canadian deposits noted above. The strataform tin/sulphide replacement deposits of Tasmania (Cleveland, Renison, etc.) must be placed in this group.

11. *"Ancient", variously modified, stanniferous sedimentary deposits*

Because, until comparatively recently, there was little evidence for the existence of "ancient" stanniferous sedimentary deposits, of which ancient tin placers are members, such deposits were not usually provided for in classifications of tin deposits. I think that it is likely that such deposits are considerably less rare than one used to believe to be the case, and that we have not recognized some of them because regional metamorphism and/or the heat and chemical components derived from neighbouring invading magma have so modified them, by effecting remobilisation, recrystallisation, etc., that they have lost much of their original identity.

Some credence is lent to the above views by Routhier's (1969) observations that 'ancient' stanniferous "sedimentary" deposits occur at Giehren, Lower Silesia; at Ipameri, State of Goias, Brazil (where the concordant deposit occurs in a pre-Cambrian sequence) and in the pre-Cambrian of Madagascar (where stanniferous felspathic lenses are included in the gneiss of the region of Esira).

The difficulty in recognizing the true identity of such deposits is made particularly clear by considering the data relating to the "schists stanniferes" of the Isergebirge district of Poland which have been provided by Mulligan (1975, pp. 51–52). According to Mulligan these stanniferous bodies "occupy a stratigraphic zone several metres thick in a series of ancient crystalline chloritic schists intruded by Hercynian granites. The zone extends intermittently for some 14 kilometres. It consists of chlorite-garnet schists believed to have resulted from metamorphism of originally argillaceous and limy sedimentary rocks". Cassiterite, accompanied by sulphides and secondary iron-rich chlorite, which is thought to have developed from garnet and biotite by hydrothermal processes, occurs in quartz veins in schists.

"Because of the complex association, and the confinement of the zone to a specific stratigraphic horizon, it is concluded that the mineralization could not have been introduced by normal hydrothermal processes. The deposits are believed to represent an ancient placer, enriched in iron and other heavy elements".

Doubtless it is more difficult to confidently assign a given deposit to this group than to any of the others, and although this is fundamentally a non-genetical classification, in this instance one would be naturally driven to seek for clues concerning the origin of a given deposit before placing it in this group.

Until much more is known about these 'ancient' stanniferous sedimentary deposits no useful sub-divisions of the group can be made.

12. *"Modern" placers*

In a classification such as this, modern stanniferous placers can be classified according to their location with respect to the hard-rock source of the cassiterite they contain, to the nature of the hard-rock source, to their sedimentary character (e.g., fluviatile, lacustrine, littoral) and to their mineralogical character.

Of course, because the genesis of a 'modern' placer can be established with a far greater degree of certainty that can that of a deposit that owes its development to the behaviour of agents of still uncertain composition and uncertain origin, the development of a classification of stanniferous placers which utilises one or more aspects of their genesis is amply justified. Thus, Varlamoff's (1975) classification of stanniferous placers, based, in part, according to the climate in which the placers developed, is wholly praiseworthy, particularly because it gives the climatic factor the importance that is rightfully due to it and which it has not generally received before.

Before leaving the question of classification it is appropriate to note that Taylor (1974b) is of the view that if the main object is to clarify concepts concerning the origin of tin deposits then "instead of attempting to classify tin deposits, *sensu stricto*, considerably more attention should be diverted to developing a classification of tin provinces". Taylor's (1974b) preliminary study of the tin deposits of east Australia demonstrated that the different provinces there "display different characteristics which may have a strong relationship to types of batholith, and levels of emplacement". That the types of tin deposit likely to be encountered in a given province are related to the levels of emplacement of the associated graniotids is surely largely correct, and it was belief in this concept that was the basis of Varlamoff's (1975) classification of the primary tin deposits.

Clearly, could a world-embracing classification of tin provinces be erected which was of such quality that provided with a limited amount of data about a given province one could forecast the nature of the tin deposits likely to occur there, with ahigh probability of being correct, it would be of the greatest value to those whose major concern was the genesis of tin deposits and to those others whose major interest lay in finding further mineable deposits. However, to draw up anything but a very general classification of provinces, or what I prefer to call sub-provinces, for even one area, say the Southeast Asian Tin Belt, "would need a vast amount of new data, for which existing funds and techniques might not be adequate. It would be necessary to know, among other things, the ages of the tin deposits and of the associated granitoids, the entire relationship between each primary tin deposit and its spatially closely related granitoid, and the detailed mineralogy and chemistry of the tin deposits and of all the rocks associated with them" (Hosking, 1974, p. 79). Finally, one would need a classification of the tin deposits. Taylor (1974b, p. 71) dislikes what he terms "artificial classifications based on structure", although why he should think such classifications are artificial defeats me: the botanists and zoologists would certainly not agree with him. In spite of his dislike for such classifications he cannot escape from their use when discussing the differences in the tin provinces of east Australia!

C. Mineralogical aspects of the patterns of primary tin deposits

The mineralogical pattern of a given primary tin deposit is essentially dependent on the species present, their size and shape, their relative abundance, the order and place of their deposition and on the physical and chemical modifications to which they have been subjected. Clearly, the possible number of patterns is enormous. The possible variations must be due first to variations in the nature of the ascending mineralising agents, which are likely to be considerable if the agents owe their character to some considerable extent to crustal rocks which have been granitised—a point which will be discussed later. Second, the variations may be due to the degree of differentiation within the magma at the time of release of the ore-forming agents. Third, the differences may be due to differences in the nature of the host rock, a fact most obvious when one compares the mineralogy of a stanniferous skarn with that of a tin deposit in neighbouring granite. Fourth, the nature of a given deposit will depend on when, and for how long, the channels along which the ore-forming agents moved were open. Fifth, it will depend on the rate of flow of the agents. Sixth, it will be governed by the presence of absence of obstacles in the channel ways which are capable of modifying the flow-rate and of causing "back-waters" and possibly turbulence to develop. Seventh, it will depend on the amount of fresh, and therefore exceedingly chemically reactive, faces, corners and edges which are present along the channel ways as a result of crushing due to repeated faulting. Eight, it will depend on the presence or absence of impounding bodies. Finally, the mineralogical pattern of a given primary tin deposit will depend to no small extent on the temperature/pressure conditions prevailing at the sites of deposition during the time of the development of the deposit (Hosking, 1965, pp. 12–13).

Generally speaking, the sequence of deposition of minerals is much the same in the various types of primary tin deposits. The usual sequence in which cassiterite is deposited before primary copper-bearing sulphides whereas lead and zinc sulphides are deposited after the copper species is, according to Nakamura and Hunahashi (1970) reversed in the Akenobe Mine, Japan. However, whilst cassiterite may occur in virtually all the types of tin deposit, other tin species are restricted, as noted earlier, to only a limited number of type of deposit. Thus, wodginite, and thoreaulite are confined to the pegmatites, malayaite to the stanniferous skarns, and the rare tin-bearing sulphides teallite and cylindrite to xenothermal deposits. In addition, the associates of the tin species vary considerably from one type of tin deposit to another. Thus tantalite is not found in considerable amount accompanying cassiterite except in the pegmatites, and the ruby silver species are extremely rare in tin deposits excepting in some of the xenothermal ones.

The usual sequence in which cassiterite is deposited before primary copper-bearing sulphides whereas lead and zinc sulphides are deposited after the copper species is, according to Nakamura and Hunahashi (1970) reversed in the Akenobe Mine, Japan.

The nature of the wallrock alteration varies according to the type of deposit with which it is associated and with the original composition of the walls themselves. Thus, stanniferous pegmatites are often surrounded by a mica-rich, comparatively narrow halo, which, on occasion, may be reasonably termed greisen. The early veins in granitic high-spots are also associated with greisen, which may be modified by the addition of chlorite, hematite, tourmaline, topaz, flurite and ore-minerals (beyond which is often kaolinised granite) and which, on occasion, may contain such a proportion of albite that it is better termed albitite, and, according to Varlamoff (1975) notable examples are to be found in Nigeria and Egypt. In Cornwall, the 'granite' in the vicinity of a carbona occurring in a granite 'tongue' at Levant Mine, Cornwall, has, according to Jackson (1975) been strongly albitised: this type of wallrock alteration is not known elsewhere in the Cornish tin-fields. Lodes of the Cornish type are frequently bounded by wallrocks, granitic and others, which have been subjected to a number of different types of alteration. On occasion the later types of alteration products develop, at least in part, at the expense of the earlier-formed alteration minerals. In such an environment the normal sequence of alteration of granitic and non-calcareous sedimentary or metasedimentary rocks is sericitisation (albitisation), tourmalinisation, chloritisation, haematisation, and kaolinisation, and associated with each, and sometimes occurring alone, is silicification. When the wallrocks adjacent to such deposits are carbonate rocks or basic ones they may be altered to a skarn-type suite of rocks, but, doubtless, on occasion, the ore bodies under review, intersect skarns that developed independently and that may be stanniferous.

Often the zones of alteration, noted above, are narrow, but when this is the case, as it often is in Cornwall, it is common to find for a considerable distance on either side of a given lode, veinlets and partings fringed by the normal alteration minerals. Such veinlets and partings tend to become more frequent as a lode is approached and hence are pointers to its presence.

In addition to the obvious signs of wallrock alteration in the vicinity of lodes of the Cornish type, there may be an envelope characterised by the presence of anomalous concentrations of the ore metals which can be revealed by appropriate trace element analyses. In Cornwall this envelope is a comparatively narrow one, often not greater than 7 metres, although anomalous concentrations of ore metals are often to be found in fractures at considerably greater distances from the ore body. In addition, such ore bodies may be surrounded by envelopes of rocks which possess anomalous thermoluminescent and/or fluorescent properties. However, Hosking and Osman Hamid (see Hosking, 1965) established that at Geevor Mine, Cornwall, anomalous thermoluminescence and fluorescence only occurred within 15 to 25 feet of the ore body, as did anomalous concentrations of tin and copper.

In many instances the gangue minerals in the lodes etc., discussed above, and the new minerals that occur in the adjacent wallrocks, are the same, so that one is justified in regarding the altered wallrocks as the extension of the lodes—the alteration having developed as the lode developed. However, this is not always the case. At St. Michael's Mount (Cornwall), for example, Hosking (1953–54) has established that the greisen pods and bands developed in the granite before the cassiterite/wolfram-bearing veins which are spatially closely associated with them Elsewhere, as for example, at Bejanca, Portugal, (Neiva, 1944, p. 121) the geometry of the greisen body and the associated veins also demonstrates that the greisen predated the formation of the veins.

The wallrock of the porphyry tin and their neighbouring xenothermal lodes that are associated with high level, later Tertiary granitoid stocks in Bolivia, displays types of alteration that are not unlike those found in Cornwall and that apparently developed in the same sequence as the Cornish types. Thus Sillitoe *et al* (1975, p. 913) note that the stocks in question display pervasive sericite alteration and that 'locally sericitic alteration grades outward to propylitic alteration, and at Potosi grades upward to silicification generated by hydraulic leaching. A quartz-tourmaline core occurs in hydrothermal breccia at Chorolque". At Mount Pleasant, New Brunswick, where a porphyry polymetal deposit is accommodated in a volcanic pile, greisenisation, and later, much more widespread propylitisation, are the dominant types of wallrock alteration, but locally silicification is important, as is later kaolinisation. However, at Mount Pleasant, the propylitisation is, I think, in part deuteric so that locally it is not spatially related to the mineralised veins. This was well shown years ago when the superficial cover was stripped from the top of the hill. In that area the major trends of tin mineralisation could not be established visually although geochemical analysis of samples taken at closely spaced intervals enabled it to be determined (Hosking, 1963). The polymetallic xenothermal veins of the Ashio Mine occur in a rhyolitic body of Neogene age which, according to Nakamura (1970, p. 238) suffered a widespread alteration 'very similar to the so-called propylitic alteration which is not spatially related to the mineralised veins. However, the veins are bordered by the following hydrothermal alteration zones, which, from each vein outwards, are as follows:-

"(i) a zone of silicification in which all feldspars are converted completely to an aggregate of released and/or hypogene quartz of various grain size, with or without some sericite,

(ii) a zone of sericitization and silicification in which all feldspars are completely replaced by sericite, containing a small amount of released and/or hypogene quartz and

(iii) a zone of chloritisation and sericitization in which all feldspars are completely replaced by chlorite and sericite, containing some released quartz."

Zoning

Mineral deposits may be so distributed within a considerable portion of the Earth's crust that one may say that they display regional zoning. The western margin of South America is an excellent example of regional zoning in which one of the zones is stanniferous. This example has been described earlier. In addition, within a tin province one may find, what Park and MacDiarmid (1970, p. 16a) term, district zoning. Thus, in Cornwall (Fig. 3), in plan, a zone containing tin lodes is often found associated with a granitic cusp and this, in turn, is surrounded by one in which copper-bearing lodes are dominant. The copper zone is, in turn, fringed by a lead/zinc one. Typical examples are associated with the granitic cusps of St. Agnes and Cligga. In Malaysia, the hard-rock deposits of the north-south-trending Kinta Valley and its eastern and western fringing granitic hills, the Main Range and Kledang Range respectively, are also zoned on a district scale. There tin, tungsten, iron and lead/zinc deposits are arranged in zones that more-or-less parallel the long axes of the granitic ranges (Hosking, 1973). In Central and West Africa the rare metal granitic pegmatites, related aplites, quartz veins (some of which bodies are stanniferous) are arranged, according to Varlamoff (1972) in and around the granite intrusions in a zonary manner. Varlamoff (1972, p. 202) concludes that "in the same metallogenic province may co-exist granitic intrusions having crystallised at different depths or at different

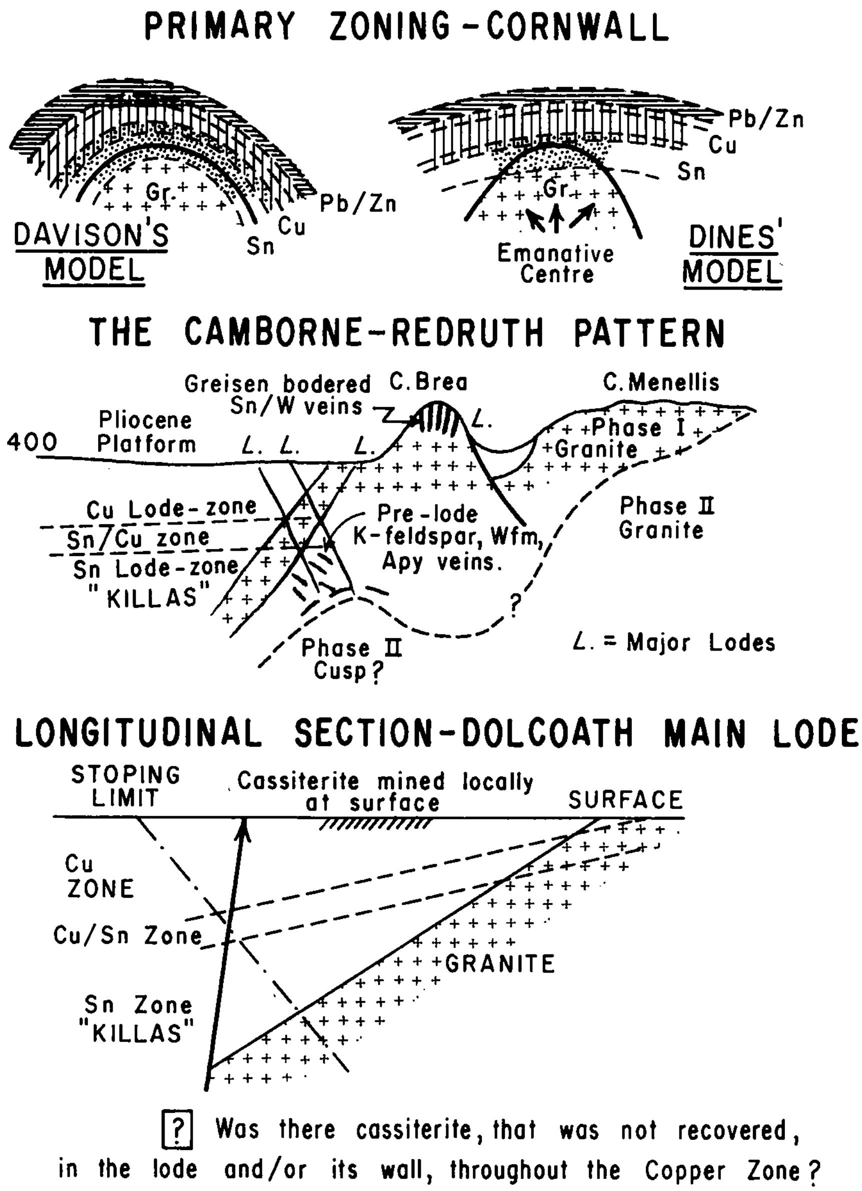


Fig. 3. Aspects of the Cornish primary zoning patterns.

geological ages. To each depth of crystallization of the granitic intrusions corresponds a specific spatial distribution pattern of rare-metal pegmatites characterised by the distance of different pegmatite types to the granite contact as well as by the dimensions of the pegmatite types and by the size of their minerals. This may outline a special zonation within a metallogenic province".

Varlamoff (1972, p. 213) points out that there are differences of opinion concerning the genesis of the different pegmatites that are organised in a zonary manner. He is of the view "that there are magmatic chambers of differentiation from which the pegmatites and the fluids or solutions responsible for albitisation, greisenization, lepidolitization, tourmalinization and mineralisation processes are successively expelled in a pulsatory manner". He also notes that "others (Nedumov, 1964) consider that the pegmatitic melt resulting from differentiation is expelled at once into the enclosing rocks, and then under its internal pressure and tectonic influence proceeds upward, leaving different types of pegmatites as it ascends".

Earlier, Mulligan (1962, p. 846) when discussing the origin of certain Canadian lithium- and beryllium-bearing pegmatites, had noted that the mineralogic character of the pegmatites varies with the distance from the "parent" granitic body. He also provided field evidence in support of his contention that there is a relationship between the regional and internal zoning of such bodies, and he remarks that the main indication of this "is the fact that the sequence of mineral assemblages from **innermost** to **outermost** dykes, in examples of regional zoning, is analogous to the sequence from **outermost** to **innermost** zones in examples of internal zoning".

Agassiz (1954) demonstrated that a pattern of zones was to be found in a stanniferous pegmatite field at Kivu. There the outcropping tin-bearing bodies are arranged in three concentric zones around a granitic mass. In zone I, the nearest to the granite, there are potassic pegmatites, together with aplites and quartz veins containing Sn, W, Au, Nb, and Ta. In the intermediate zone 2 there are stanniferous sodium- and lithium-rich pegmatites, whilst in the outermost zone 3 quartz veins alone occur: these contain Sn, Au, Fe, As and S. Agassiz's diagrammatic section suggests that the bodies may be vertically zoned, and one which at the surface may show zone 3 features may display first zone 2 and then zone I with increasing depth. I find it difficult to believe that there is definite evidence in Kivu, or anywhere else, that tin-bearing veins exist which are extensions of pegmatites.

At this stage it is relevant to consider in some greater detail the zoning patterns found in Cornwall as this region has been considered the type area of such hydrothermal phenomena.

Davison (1925) (Fig. 3) was of the opinion that in Cornwall a series of somewhat overlapping zones were developed in the vicinity of many of the original high spots of the granitic batholith that forms the backbone of the County. He believed these zones were approximately parallel to the granitic contact and that a tin zone was overlain and in part overlapped by a copper zone and that the copper zone was in turn overlain and part overlapped by a lead/zinc zone. Removal of portions of the zones by denudation provided, in plan, a variety of modifications of the original pattern of which the St. Agnes and Cligga ones noted earlier are common.

Dines (1934) (Fig. 3) provided field evidence in support of his view that Davison's model was wrong. He held the view that the various zones, which were spatially related to granitic cusps, were generally considerably flatter than the associated granite contacts, and that the higher the zone the greater its lateral extent. Dines, further, was of the opinion that the deposition of certain minerals in zones was temperature determined. It was due, in his opinion, to the temperature gradient that was established between the granite and the surface as a result of the invasion of the hot granitic magma.

Long ago (Hosking, 1964) (Fig. 4) I pointed out that Dines' view was inacceptable particularly because neither the early felspathic wolframite-bearing veins nor the greisen-bordered stanniferous swarms fit completely into his regional primary zoning model. At South Crofty Mine, for example, wolframite does not occur in the major lodes below the 260 fathom level, yet it, and arsenopyrite, are plentiful in the earlier felspathic veins at the 335 fm. horizon where they are intersected by cassiterite/quartz/chlorite/fluorite lodes. Greisen-bordered swarms are, in a sense, not related to the complex hydrothermal lodes which commonly flank the cusps in which the former occur. The paragenesis of a given swarm is virtually the same as that of the complex lodes and there may be little difference in the kinds and numbers of species present. Furthermore, a given swarm may show some zoning, as that at Cligga, and this is quite independent of that displayed by neighbouring complex lodes. At Cligga, for example, complex zinc- and copper-bearing lodes occur in the hornfels immediately adjacent to that part of the cusp which contains quartz/tourmaline and cassiterite/wolframite/quartz veins. On occasion, also, branches of the complex veins **appear** to have invaded the cusp and in part to have been accommodated in it as a result of the early greisen-bordered veins being reopened. However, the Zn/Cu-bearing veins in the cusp may **not** be entirely or partially extensions of the Zn/Cu lodes in the hornfels, and within the cusp the inverted zoning (quarts/tourmaline veins near the contact: below them, later Sn/W veins, then still later Zn/Cu veins lying deeper in the cusp) may all have developed during a pre-lode stage of mineralisation when successive and differing mineralising fractions deposited their components at progressively lower levels and essentially within the confines of the igneous mass. In any event, it is quite impossible to employ Dines' geoisothermal model, in which the granitic body is the sole source of heat, to account for the entire relationship.

I concluded (Hosking, 1964, p. 232) that if temperature were the dominant factor that determined where a given mineral would be deposited then "the lack of conformity between the distribution of minerals in closely spatially associated but distinct types of deposit, as well as certain mineral associations noted in some of the individual ore bodies, can in part be accounted for if it is assumed that the regional temperature gradient between the hot granite and the land surface was not the dominant controlling factor but that the gradient established along each fracture system as a result of hot ascending solutions loosing heat progressively to the wallrock was". (See footnote.)

This suggestion is in no way incompatible with the observed regional primary zoning patterns, as hot solutions derived from a deep source, and ascending similar fractures in essentially the same rock type, would result in zones which are much flatter than associated cusp/killas contacts. Moreover, if it is held that a temperature gradient due to the loss of heat from ascending solutions was the dominant factor which determined where given minerals might be deposited, it is to be expected that there would be a lack of correlation between the deposition of species in the metallised felspathic veins, greisen-bordered vein swarms, and the complex hydrothermal lodes, as they were developed at different times and perhaps from different sources which themselves differed greatly in size and in disposition with respect to the contemporary land surface. ..... In addition, local fluctuations in the temperature of developing lodes

I am aware that there are some who think that heat loss to the wallrocks would not result in a marked temperature gradient along a fracture if the ascending agents were fast-moving. I am also aware that heat might be lost in a significant way as a result of throttling and boiling.

would readily explain the various spatial relationships existing in similar ore bodies between two species, each of which was represented by two generations."

It must be stressed that whilst I believe the above model I have presented to account for the general details of primary zoning in the Southwest of England I am sure that it cannot always be used to account in a satisfactory way for the primary zoning that is encountered elsewhere. Thus, for example, if Strauss (1954) is correct in believing that the zoned cassiterite-bearing pipes in the granite of the Zaaiplaats-Groenfontein tin field (S. Africa) "developed when granite was passing from a still partly plastic to a solid state" (p. 142) it may well be, as Strauss believes, that the zoning in individual pipes was determined by where and how the pipes developed with respect to the geoisotherms established as a result the emplacement of the hot Lease and Bobbejaankop granites (in which the pipes occur) beneath the cool Main granite. Strauss' figures 58 and 59 (p. 143) illustrate this view. However, if Sóhnge (1963) is correct in his view that the Zaaiplaats field developed by granitisation of bedded formations containing replacement deposits of the Rooiberg type, together with mineralised fractures and fissures, which were converted to the pipes, etc., now found there, Strauss' view of the zoning will need to be modified or even completely replaced by another.

That temperature is probably the dominant factor in the development of the Cornish primary zones was further indicated by the fact that Sawkins (1966) found that the filling temperatures of 24 samples taken from ore deposits of the area demonstrated that a significant difference in the temperature of formation existed between tin, copper and lead/zinc mineralisation. Sawkins' findings were confirmed by Bradshaw and Stoyel (1968) who determined the filling temperatures of over 1,000 inclusions occurring in samples collected from 185 Cornish mineral vein localities. Bradshaw and Stoyel (1968) also concluded that "a definite and fairly restricted temperature zone exists for each mineral": that "after careful sampling of a vein, the maximum filling temperature obtained is an indication of the upper limit (in terms of temperature) of the portion of the zone which is here represented", and that there is evidence in support of the view "that filling temperatures in vein material can be used to determine the relationship between a particular vein and the economic zonal sequence". They were also of the opinion that "quartz can be used to obtain a reliable filling temperature for a mineral with which it is intimately associated, provided that the paragenetic sequence is studied with great care".

So the above fluid inclusion studies strongly support not only the view that the disposition of the primary zones is primarily temperature controlled, but also that mineralisation took place under conditions of waning temperature, and in each mineralised area in such a way that the earliest minerals that were formed were deposited closest to the assumed source of the ore-forming agents (the 'emanative centre' of Dines). However, there is no doubt that the development of the hydrothermal deposits of the Southwest of England was far more complex than the above studies suggest, and Jackson and Rankin (1976), for example, are in agreement with this view having established that in the apparently simple system of greisen-bordered veins characterised by the presence of cassiterite, wolframite and a little stannite, and occurring in the St. Michael's Mount granite, the assemblage of fluid inclusions and their composition and abundance are extremely complex, and that 'individual cassiterite crystals show a temperature variation from margin to core of 340–400 °C,' which is "the same as the total range in temperature at which cassiterite was deposited in the whole vein system". E.B. Yeap (personal communication) has established that a similar complex state of affairs exists in some of the veins of the Selangor tin field.

In a very stimulating paper, filled with much new thinking, Hawkes (1974) provides strong evidence in support of the view that the tin deposits of the Southwest of England, that are spatially related to granites emplaced in late-Carboniferous times, were not developed until about 20 m.y. later, in Lower Permain times, when erosion had probably part-unroofed the eastern protion of the batholith, and at about the time when the elvan dykes were being emplaced. In Hawkes' view (p. 1139) at this time ascending ore-forming agents mixed with the cooler, more oxygenated, acid connate and ground waters in the topmost 1.5 to 2.0 km of the crust, and then 'the lengthy process of ore deposition commenced'.

Whilst agreeing that temperature, pressure, ore-fluid chemistry and wallrock composition were important controls of the mineralisation, he suggested that 'the changing contours of the L. Permian land surface, especially those immediately above individual 'emanative centres', was also an important factor. He further suggests that it is likely that the apparent reversals of zoning seen in some lodes ..... were connected with the rapid erosion of overlying rock during intervals between successive periods of ore deposition". He also observes that 'one useful indication of the contours of water tables and general topography could be the interface between the vertically disposed tin and copper zones in neighbouring lode complexes. ...... the slope of the interface commonly shows a relationship sympathetic to the slopes of country rock-granite contacts. Usually this feature is ascribed to a temperature gradient related to the local pluton or to the batholith. It may simply reflect the presence above of L. Permian pediment spreads from higher ground over the batholith crest line".

One cannot but be attracted by many of Hawkes' views, but it would be a mistake to embrace all of them without question. In Cornwall, there is, for example, evidence that some mineralisation predated the termination of the granitoid magma invasion, and much more dating of the lode and vein components is needed before a reliable mineralisation model can be assembled. However, of particular importance is the fact that Hawkes' studies provide strong reason for giving the most serious consideration to the possibility that in the Southwest of England mineralisation and volcanism may be closely related. Hawkes' arguments, together with the occurrence of some distinctly telescoped tin deposits, such as those of Wheal Baddon and Penberthy Croft, and the considerable number of wood-tin occurrences, suggest that the style of mineralisation is, perhaps, much closer, to the central and southern parts of the Bolivian tin province than one used to think. Did Cornwall once have southern and central Bolivian type tin deposits that have since been largely destroyed by denudation? Could the greisen-bordered stanniferous lode/vein swarm at Ding Dong Mine in the Land's End granite be the roots of a porphyry tin deposit?

In tin provinces, such as those of Central and Southern Bolivia, and Japan, which are characterised by the presence of xenothermal deposits and with which porphyry tin deposits might occur, as they do in Bolivia, zoning, which may depart considerably from that encountered in Cornwall, may be present. Because xenothermal deposits were formed comparatively near the surface, often within complex fracture systems within which high temperatures were attained at a fairly early stage of the period of ore-body development, many of the deposits display marked telescoping, and it is reasonable to expect that if zoning is to occur it is likely to be the lateral type that will be dominant. Turneaure (1960, p. 583) makes the following pertinent remarks: "Vertical zoning, marked by a consistent change in mineralogy with depth has not been clearly demonstrated in the (xenothermal) deposits of Central Bolivia, but some semblance of vertical zoning is noted in the tin-silver deposits of Potosi and Oruro. Lateral zoning .... on a local scale is suggested by mineral distribution at Llallagua and Huanuni". (The vertical zoning to which he refers is indicated at Potosi, for example, bythe occurrence of silver above tin and of cassiterite **above** stannite). Concerning lateral zoning Turneaure states (1960, p. 588) that at Llallagua the tin-bearing zone "is partly surrounded by one in which several low-grade sulphide veins have been explored", and at Huanuni, also, a tin zone is surrounded by one in which sulphides are dominant.

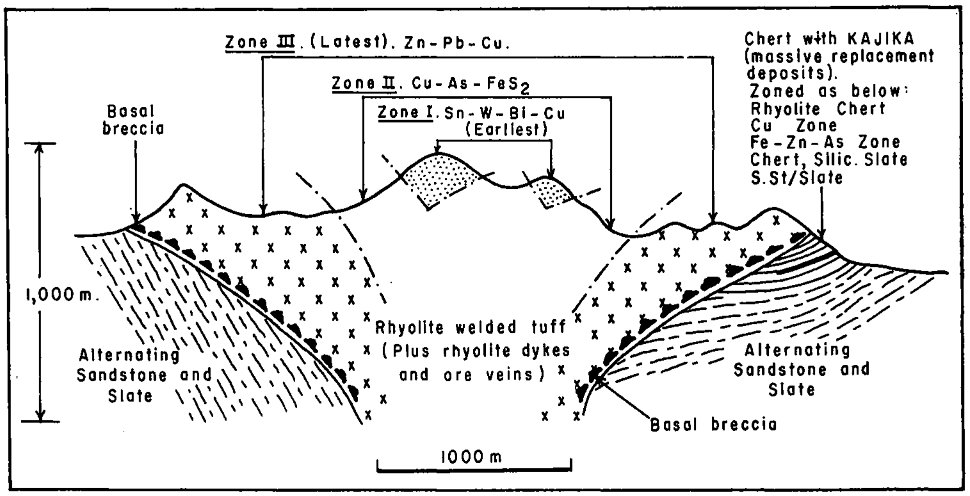


Fig. 4. Primary zoning in the Ashio Mine, Japan (sketch). (Based on data after Nakamura, 1970, 231–246).

In the Ashio Mine, Japan (Fig. 4), in which the veins are largely confined to a funnel-shaped mass of rhyolite-welded tuff and rhyolite, unusual lateral zoning occurs. The earliest Sn-W-Bi-Cu central zone is flanked and underlain by the intermediate Cu-As-Zn zone, and this, in turn is flanked by the marginal Zn-Pb-Cu-As zone (Nakamura, 1970). In the Akenobe Mine, Japan (Fig. 5) the state of affairs was also unusual. There, according to Nakamura and Hunahashi (1970) the Pb/Zn zone was the first to develop whilst the Sn/W zone was the last.

Other factors that controlled the distribution of tin, etc., in the primary deposits

Temperature was by no means the only factor that determined the general distribution of tin in the Cornish and other fields and the nature of the metal distribution patterns within individual ore deposits. The importance of some probable controls such as pressure of one sort or another, and the degree of availability of connate and groundwaters and local variations in their composition, are very difficult and perhaps, on occasion, virtually impossible to assess. Fortunately a number of other factors that exert a controlling incluence on the patterns under review are more amenable to study and some of the more important of these are briefly noted and discussed below.

1. *Factors associated with fracture and fault development*

For a lode of the Cornish type to develop there must be an adequate passage way

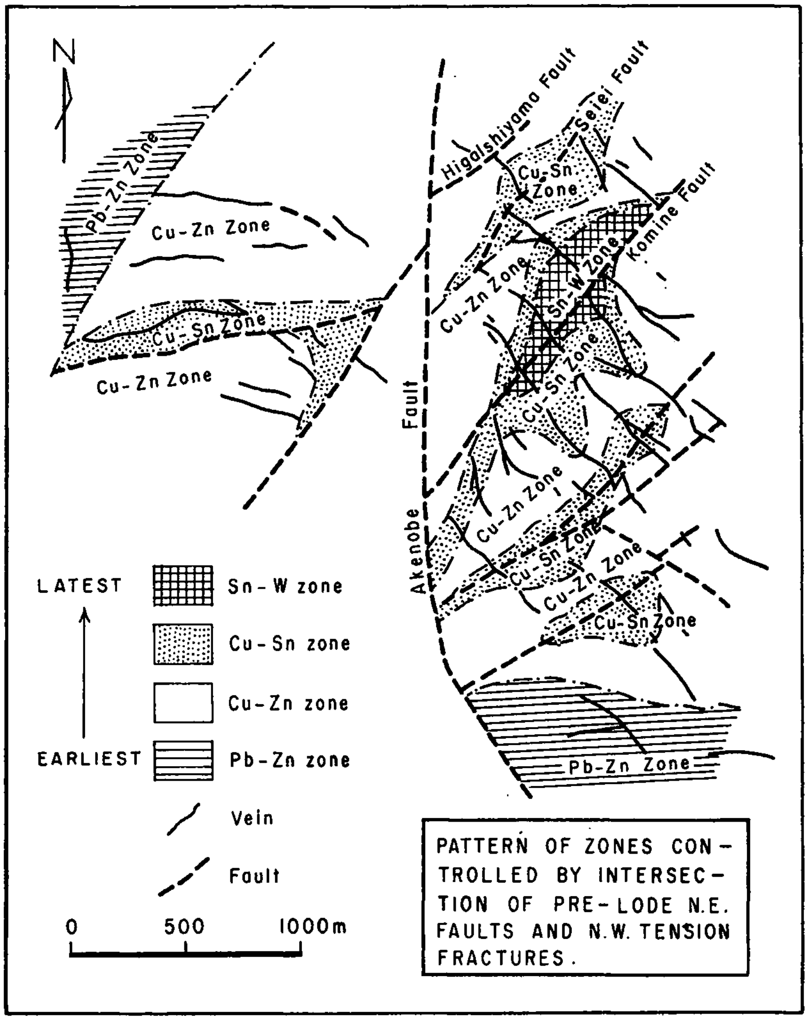


Fig. 5. The horizontal zoning in the 2L-level at the Akenoke mine. (essentially after Nakamura and Hunahashi, 1970, p. 226).

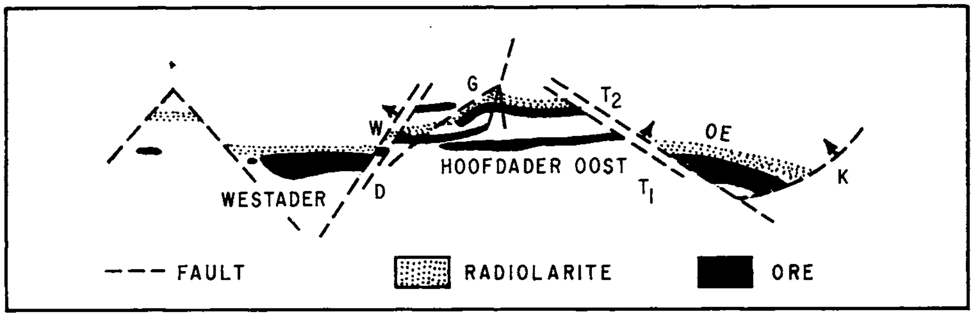
for the ascent of the mineralising agents. This is usually a fault. For a strong tin lode to develop the passage way must be open, ideally for the whole of the time that the tin-carrying agents are available. If the passage way remains open, or is reopened over a long period, minerals other than cassiterite may be deposited in the tin zone and so, in the extreme case decrease the value of the lode even to a point when it is of little or no economic value. If the passage way is not open throughout the zone in which cassiterite is capable of being deposited and when the tin-depositing agents are available, then the ideal zonal distribution pattern will be modified. In part this may be the reason why when points indicating the upper economic limits of tin ore in the South Crofty Mine (Cornwall) lodes are joined a markedly zigzag line results.

On the other hand a suitable passage way may transect the whole of the zone suitable for the cassiterite deposition and be open during some of the time when cassiterite-developing agents were available, and yet cassiterite might not be found throughout the space suitable for its deposition simply because not enough tin was introduced into the site. That this is a distinct possibility was established by me (Hosking, 1954) as a result of examining a drusy pegmatite at Trolvis Quarry (Carnmenellis, Cornwall). In this pegmatite the varieties of late-deposited minerals that occurred on the undersides of feldspar baffles in the druse decreased from the bottom to the top as did the absolute amounts of the various species.

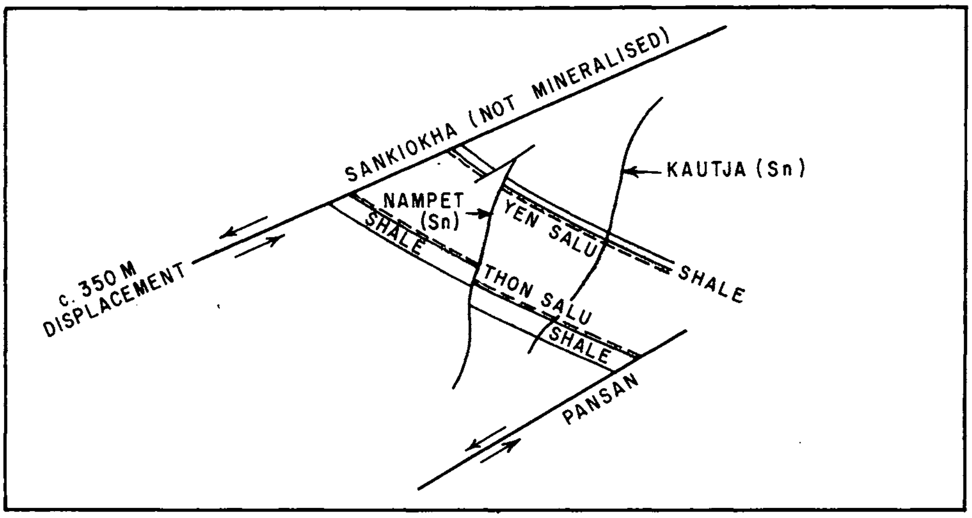
Most of the Cornish lodes are basically normal faults, as are those at Pahang Consolidated Mine (Malaysia), and in both instances the rich parts of the lodes are those with the steepest dip. It is well known that when a fracture of varying dip becomes a normal fault the steepest parts are the widest open parts of the fault. Whether the rich parts are the steepest parts of the lodes simply because these were where open places were available in which ore minerals could be deposited or whether there were other factors which partly, possibly largely, determined this relationship, remains uncertain. Often the rich parts of lodes owe their development to no small extent to replacement of the wallrock and fragments thereof. It may be that the deceleration of the ore-forming agents on entering the open spaces is an important factor in ore shoot development.

Drag during descent of the hanging-wall may cause the wall to be fractured and if this happens when cassiterite-depositing agents are available the wall may be locally converted into rich ore. One of the Old Wheal Vor lodes and the Towanrath lode of Wheal Coates possessed this feature (Hosking, 1970a).

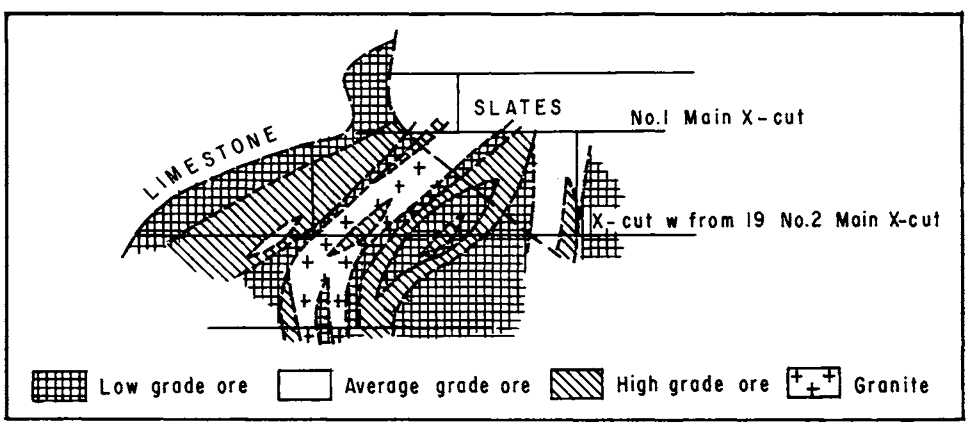
On the district scale faulting may exert marked controls on the mineral distribution patterns in a number of ways. Thus, for example, it is likely that many of the tin lodes in Cornwall, of the Pahang Consolidated Mines, and of Kelapa Kampit Mine (Belitung) (Fig. 6a–e) have been developed along tension fractures and second order shears that have been generated between two wrench faults (see Hosking, 1974, p. 56–57). Such wrench faults, apart from playing a major part in tin lodes genesis also controlled their strike extent: in other words they behaved as impounding bodies. Post-mineralisation faults may disintegrate the original mineralisation pattern, and on occasion allow it to be further modified by providing passage ways and sites of deposition either for minerals associated with a further phase of mineralisation that may, genetically speaking, be quite unrelated to the first, or for dyke-creating magma. Thus, Both and Williams (1968) established that only after due allowance was made for post-mineralisation faulting could the earlier postulated zonal relationships of Zeehan field, Tasmania, be substantiated. In addition, these workers also concluded that locally, in the Queen Hill area, the mineral distribution was due to superimposed zoning, the later phase of mineralisation perhaps being associated with a separate granitic intrusion. On the other hand, they thought that the intrusion might not exist and that the second mineralisation "might be zoned around a favoured channelway or system of channelways extending in depth to the granite surface. Rapid flow of hydrothermal fluids along such a system could bring them to this area at higher temperatures than early fluids which migrated more slowly, thus accounting for the high sphalerite-iron contents and the presence of tin minerals which normally would have precipitated closer to the parent intrusion". There is reason for believing that in the Southwest of England some of the lead-zinc lodes which strike at about right-angles to the neighbouring tin- and copper-bearing ones, and which, on occasion, as at



(a) Simplified diagram of Main Lode 3rd Level Klappa Kampit Mine, Billiton, to show more clearly the relationship between mineralisation and tear faults (after Adam 1960)

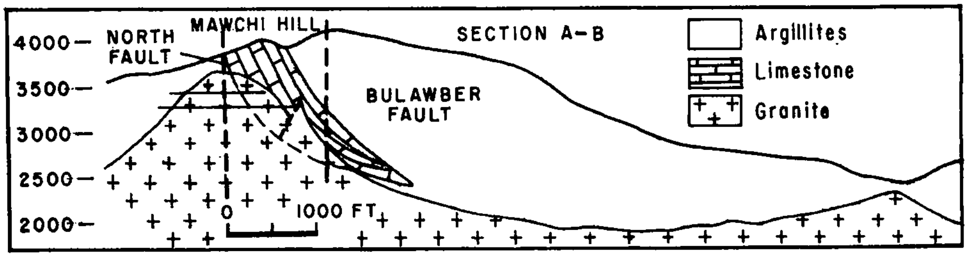


(b) The tear faults Sankiokha and Pamsan, the sigmoidal tension fractures Nampet and Kautja, and the bed-view Yen Salu and Thon Salu, Klappa Kampit mine Field, Billiton (after Adam 1960)

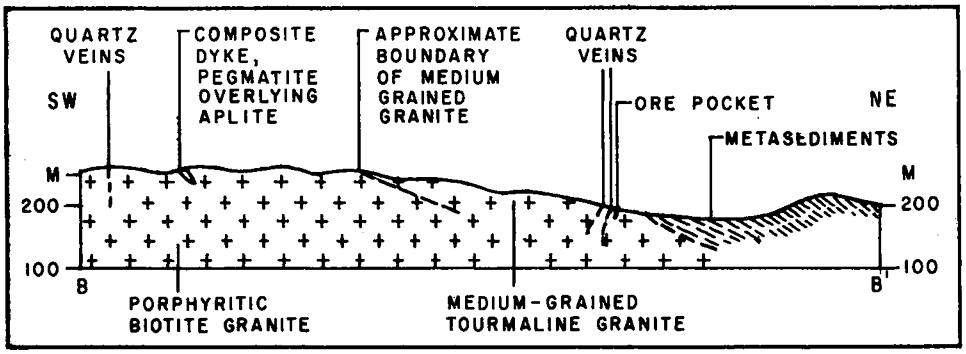


(c) The ore shoots of vein 190, Mawchi Mine, Burma (after Hobson, 1940)

Fig. 6 (continue next page)



(d) Section across the Mawchi Mine, Burma (after Hobson, 1960)



(e) Longitudinal section, from South-West to North-East, across the Haad Som Pan Tin Field,

Fig. 6. Diagrams indicating the role played by impounding bodies in determining the disposition of primary tin deposits in South-East Asia. (Hosking, 1974).

Wheal Budnick and in the Porthtowan-Nancekuke coastal section, intersect the earlier tin and copper lodes, were developed from faults that were mineralised during Mesozoic or Tertiary times (Hosking, 1964, p. 222–223). Several of the lodes at Pahang Consolidated Mine have been disrupted by post-mineralisation (rhyolitic?) dykes. The Gakak 3 Extension Lode has been longitudinally split into two pieces by such a dyke which possibly entered along a fault and which profoundly altered some of the components of this tin lode.

2. *Igneous events post-dating the original mineralisation*

Immediately above is an example of the sort of thing I wish to discuss at this stage. There are a number of ways in which igneous events that post-date a phase of mineralisation can modify the existing mineralisation patterns, and several of them have been postulated to account for one aspect or another of tin distribution patterns. Thus, Pereira (1963, p. 17–18) suggests that the quartz-cassiterite veins that occur in phyllites overlying a mobilised gneissic dome in the Karagwe District of Tanzania owe their origin to the remobilisation of tin in the gneiss that was effected during the granitisation ofthe gneiss which lead to the generation of 'cross-cutting intrusive granites. Pereira's Figure 7 (p. 17) illustrates the general geological features of the field.

The Castlc-an-Dinas Mine of Mid-Corneswall developed to exploit a single, near-vertical lode which consisted essentially of quartz, wolframite and loellingite. Cassiterite occurred in the hornfels walls adjacent to the lode but was not present in sufficient quantity to be worth recovering. This lode was invaded by a granitic tongue and the rich parts of the orebody halo this tongue. I am of the opinion that the present distribution of heavy minerals in this lode, and possibly the cassiterite in the wallrock, is due to the invading granite rejecting a portion of those lode components that it could not incorporate in the lattices of its minerals, and in such a way that they accumulated in the form of a heavy metal front. It might be added that some of the wolframite caught up by the advancing granite resisted assimilation and is present in it as xenoliths (Hosking, 1964, p. 234).

In any tin province in which granitoids of distinctly different ages are known or are likely to be in close association, as appears to be the case in Malaysia, then it seems possible that the later granitoids may modify the mineralisation patterns associated with the earlier granitoids, in a number of ways. These have been discussed by me at some length elsewhere (Hosking, 1973) and so it is only necessary to remark here that in such circumstances the older hard-rock tin deposits may be assimilated by the later granitoids, or their mineral content may be modified by additions from the later granitoids: other possibilities are presented in the paper noted above. Even when one is dealing with mineralisation associated with polyphase granitoid intrusions rather than with granitoid intrusions of markedly different geological ages, complications in the distribution patterns of tin and related metal deposits may arise which I think have not been given the prominence in the literature that they deserve. Thus, at South Crofty Mine, Cornwall, two swarms of feldspathic veins, containing wolframite, arsenopyrite together with a little cassiterite are locally cut by later lodes and veins containing quartz, chlorite, cassiterite, etc, (for a detailed description of these deposits see Taylor, 1969). I am of the opinion that these felspathic veins have developed within, or above, high spots on the phase 2 Carnmenellis granite which are also the loci of development of the much more important tin/chlorite lodes (Hosking, 1970a, pp. 1160–1161). These felspathic lodes are over 300 metres below the contact of the phase I granite with the metasediments. Locally on the high spots of the phase I granite there are groups of greisen-bordered tin/tungsten veins of very limited extension down dip: they are exposed, for example, at the top of the Corn Brea granite ridge and are known to have occurred in the granite of the mine at Camborne Beacon as I have found material from such veins on the waste dumps there.

Recently (Hosking, 1977) I gave reasons for believing that the swarm of greisen-bordered tin/tungsten veins of the Tikus Mine, Belitung, which are situated in the middle of a large peneplained granitic mass, are associated with the high spot either of a later phase granitoid or of a granitoid of distinctly later geological age. It was this suggestion which prompted the dating of the muscovite of the greisen by Jones *et al* (1977). These workers discovered that the mean age difference between the greisen and the Belitung granitoids is 20 m.y. and they concluded that this indicates that the tin mineralisation is not a simple late-stage event in the emplacement of Late Triassic granitic plutonic rocks, "but the reason for the difference is not known at present" (p. 751). It is of interest to note that this interval of time is the same as that between the emplacement of the granites and the development of the tin lodes in Cornwall. (See Hawkes, op. cit..)

3.*Impounding structures*

Elsewhere I have defined an impounding structure as a geologic structure that completely prevents, or severely restricts the movement of some or all of the components of a mineralising agent in certain directions (Hosking, 1971a, p. 54). In a series of papers MacKay (1925, 1946, 1948) emphasised the important role played by impounding structures in the localisation of ore. He limited his observations to lithologic barriers and he held the view that these behaved in a manner somewhat analogous to that of a semi-permeable membrane, allowing only the smaller ions to pass through. He believed that the reason why such barriers were much more obvious controls during the deposition of, say, lead and mercury deposits than tin deposits was because the hydrated lead and mercury ions were smaller than the tin ones and hence a much more efficient net was necessary to 'catch' the former. This view was not received with much enthusiasm amongst the more chemically minded.

In my 1971 paper, referred to above, I pointed out that a great quantity of solution must move into and out of a site at which a hydrothermal ore-body was developing, and in those cases in which the ore developed below a lithologic barrier it was likely that in some instances the ascending mineralising agents did move into the site of deposition along well-defined channelways and from the site through the barrier via rather restricted fractures. However, I also suggested that perhaps a convection cell developed below the barrier which permitted the pregnant ore-forming solution to discharge its ore-forming components at the 'low-temperature' site below the barrier and then to descend, via parallel channel-ways, carrying with it the unwanted products from the replaced rock and, at deeper horizons, exchanging them for ore-forming components. Figure I (p. 61) of the paper illustrates this crude model, which in spite of its faults anticipates the much more refined and convincing convection models of ore deposition proposed of Henley (1971) which were based on temperature data, etc., from the New Zealand hydrothermal areas.

It is not difficult to provide examples of lithologic barriers from the tin provinces and I have noted some examples elsewhere (Hosking, 1970b, 1971a and 1974). However, it is relevant to provide some examples here. In the Mawchi Mine, Burma (Fig. 7) the rich tin/tungsten lodes are confined to the apex of a granitic cusp where the later is in contact with marble, but they extend beyond the granite where the capping is argillite. At Haad-som-pan, Thailand (Fig. 7) tin deposits occur in medium-grained tourmaline granite and beneath impounding metasediments. The Levant carbona (Jackson, 1975) and the South Crofty No. 12 lode are both stanniferous replacement bodies in granitic tongues which in each case, are associated with barren feeder channels. At Parbola Mine (Cornwall) the stanniferous veins are confined to a porphyry dyke, at the Wherry Mine (Cornwall) the tin ore have developed in a porphyry dyke where a feeder system intersects it, and at the Magdalen Mine (Ponsanooth, Cornwall) a metadolerite was converted to a tin deposit mainly because it fractured more readily than the metasedimentary rocks surrounding the metadolerite, and because the feeder channel was constricted beyond it.

On occasion the distribution of cassiterite within primary deposits is such as to suggest that it was controlled, at least in part, by an impounding body which has since been removed by erosion. Thus, the uppermost parts of the Mulberry vein-swarm (Cornwall) were those richest in cassiterite. The same observation may be applied to the greisen-bordered veins capping Kit Hill. In both cases any impounding body that was originally present has been removed. It is not uncommon for cassiterite to accumulate in the apices of deposits. Thus, in the Roskear Section of the South Crofty Mine the cassiterite in the Complex Lode, which dies out beneath a greenstone body, is concentrated in the apex. Here the cassiterite was deposited (impounded) within what was originally essentially a quartz-potash feldspar-wolframite body. Derry (1930) describes several examples from East Manitoba in which cassiterite is markedly concentrated in the apical parts of arch-shaped pegmatites, whilst Agassiz (1954) records that a number of pegmatites that he investigated in Zaire were characterised by the fact that cassiterite had concentrated beneath the roof. However, cassiterite is not always so disposed in pegmatites. At Kamativi, for example, the cassiterite in the flat-dipping pegmatites is normally largely concentrated just above the quartz-mica footwall selvedge, whereas pegmatites with a high cassiterite concentration near the hangingwall selvedge are less coomon (Fick, 1960, p. 479).

As noted earlier, pre-lode faults may also behave as impounding bodies, as at Geevor Mine (Garnett, 1961) and the Wheal Vor area, Cornwall and at Kelapa Kampit (Belitung).

4. *Further factors that may control the distribution of cassiterite in primary deposits*

The deposition of cassiterite may result from the progressive hydrolysis of the complex $Na_2Sn(OH, F)_6$ under conditions of changing pH which the ascending tin-bearing agents experince (Barsukov, 1957). This is referred to again later. Other factors which may be involved in the development of mineral deposition patterns, some of which have been briefly referred to earlier are, in Bateman's (1960, p. 315) opinion 'pressure, concentration, relative concentrations, reactions with wall rock, reactions within the solution causing progressive precipitation, chemical complexes, and other factors ....".

In this section in which zoning has been given considerable prominence it is important to emphasise that zoning is not to be found in all tin provinces. In spite of some early views to the contrary, obvious zoning is virtually absent from ore-bodies of the Tin Belt of Southeast Asia. It has been claimed that the lodes of both Pahang Consolidated and Klappa Kampit mines were, perhaps, somewhat richer in copper in their upper parts than elsewhere, but apart from this possibility ore from any given lode from either of these mines varies but little from horizon to horizon below the zone of supergene alteration. Perhaps this lack of zoning indicates that at any particular time during the period of mineralisation the temperature gradient within any developing lode in these mines was very flat.

Further details of the distribution of cassiterite in primary deposits

Generally speaking, only in hard-rock, underground mines working well-defined lodes in a modern way are sufficient data collected, and in such a way as to allow a reasonably clear picture of the distribution of cassiterite to be established by the use of Conolly diagrams, and the like, such as have been employed to considerable advantage by Taylor (1966) at South Crofty Mine and by Garnett (1966) at Geevor Mine, in Cornwall. The collection of data in the manner carried out in these mines, and their subsequent analyses, enable extrapolation to be made beyond the working limits of the mine and emphasise the spotty nature of cassiterite distribution even within the ore-shoots. Such work also serves to remind one how cautious one must be when endeavouring to establish the characteristics of such ore-bodies solely from the results of diamond-drilling. Such work also provides clues as to why the ore-shoots are where they are. It does not, however, tell us how the ore-shoots developed. Now one knows that extensive geothermometric investigations, isotope studies, trace-element analyses and the like are necessary before a dynamic picture of the evolution of a tin lode or a system of lodes can be obtained. There is an urgent need for much more work of the type carried out, in the Bolivian tin-fields, by Kelly and Turneaure (1970), and for detailed trace-element studies of the components of individual lodes that have, as a result of underground mining, been exposed over considerable dip- and strike-lenths. The results of such work, supplemented by ore-microscopy, and the whole interpreted in the light of the results of experimental work on tin mineral systems and related mineral systems, such as is being carried out for example by Moh (1977) and his colleagues, would, within a decade, provide us with something approaching a real understanding of those phases of the development of tin deposits which took place more-or-less at the sites of deposition.

D. **Relationships between tin distribution patterns and igneous rocks**

In this section I shall deal with the relationships between the tin deposits and the granitoids because my concern is with tin deposits of economic importance. Therefore, I shall not discuss the occurrence of stannides in basic rocks such as those of the Merensky horizon, nor shall I mention further those tin deposits of economic importance that occur in basic rocks, such as those in the metadolerite of the Magdalen Mine, Cornwall, for which there is strong evidence that the tin was introduced subsequent to the emplacement of neighbouring granitoids. Furthermore, I shall *not* try to explain any of the phenomena presented here in terms of plate tectonics.

As in earlier papers (Hosking, 1967 and 1974) I shall consider, in turn, the spatial, temporal, and chemical/mineralogical aspects of the subject.

The spatial aspect

That there is a close spatial relationship between primary tin deposits and granitoids is beyond doubt.

Within the tin provinces of orogenic regions tin deposits are commonly closely associated with granitic cusps and at least in some provinces e.g. South-west England (Hosking, 1967) Portugal (Neiva, 1944), the Herberton Tinfield, North Queensland (Taylor and Stevenson, 1972) such cusps are, in fact, the high-spots on granitic ridges with undulating crestlines.

Mineralisation within the apex of the cusp may be quite variable, but it often takes the form of a swarm of cassiterite-bearing veins and greisenisation and/or albitisation is also usually much in evidence there. Such deposits are of common occurrence in, for example, the southwest of England, Czechoslovakia and the Tin Belt of Southeast Asia. Less commonly, tin-rich lodes, rather than veins occupy the apex of a cusp, as for example, at Mawchi (Burma). Frequently, also, swarms of veins of lodes develop over, rather than within the cusp. Aberfoyle Mine (Tasmania) provides a definite example, whilst in many other areas it is thought that a similar state of affairs occurs although the cusp has not been proven to exist. Thus, the swarm of cassiterite-bearing veins at Mulberry Mine (Cornwall) and Klian Intan (Malaysia), and the lodes of Kelapa Kampit, are all thought, at least by me, to halo buried cusps. Often these veins and lodes that are associated with cusps are almost entirely exocontact or endocontact in character, but on occasion, as at Beralt Mine (Portugal), the tin-bearing lodes extend through the apex of the granitic cusp to considerably beyond its contact with the country rock.

Stanniferous skarns are also prone to develop in the neighbourhood of cusps as, for example, in the Lost River Area, Alaska (Sainsbury, 1964).

In Cornwall, and probably elsewhere, the stanniferous hydrothermal lodes, which are by far the most important hard-rock sources of tin in the County, strike approximately parallel to granite ridges, as do the porphyry dykes which generally pre-date the lodes. These lodes often appear to be richest in the general vicinity of cusps, but this is not always the case. In the St. Agnes area, for example, the richest lodes are found not near the exposed cusp but considerably to the east of it, in the vicinity of Trevaunance Cove, where fracturing has been most intense. As noted earlier, cusps near which neighbouring lodes are richest may not be exposed at the surface, and in areas characterised by the presence of polyphase granitic intrusions, or by the presence of granitic intrusions of widely differing ages, the mineralisation of importance may be most closely related to the topography of a granitic body which is completely hidden beneath an older granitic mass. The situation at South Crofty Mine (Cornwall), which is noted earlier, seems to support this view. There seems to be little doubt that there is a distinct relationship between the original topography of granitic intrusives and the disposition of primary tin deposits. It also seems that the original topography of the granite was determined by the moulding action of the invaded rocks and the disposition of pre-granite faults. It is appreciated, of course, that the invading granite was capable of deforming the moulds. In support of this one can cite Cornwall where the centres of tin-fields and, therefore, sites of the associated cusps, exposed or buried, occur at the intersections of certain NE-SW and E-W lines which are the major strike directions of the sedimentary rocks that were invaded by the granite. (See Hosking, 1967, Fig. 4, p. 297).

Neiva (1944, pp. 235–236) earlier recognized that there was a relationship between the disposition of the Portuguese primary tin and wolframite deposits and the original topography of the granite, which, in its turn was dependent on the manner of folding of the rocks which it had invaded, as he remarks that "there is a parallel disposition between the axes of metallization, the elongation of the granitic intrusions, the Agnotozoic and Palaeozoic formations and the orientation of Hercynian folding ..... The axes of metallization of primary deposits of cassiterite and wolframite are interdependent with the directions of Hercynian tectonic".

In central and southern Bolivia, where the well-documented xenothermal silver-tin deposits occur, the mineralisation is associated with high-level Tertiary stocks that range in composition from dacite to quartz latite. These stocks are believed by Sillitoe *et al.* (1975) to have been overlain by stratovolcanoes at the time of their emplacement and they record that 'coeval volcanics are preserved at Oruro and Chorolque, and perhaps also at Potosi. A mineralised edifice remains at Chocaya and is believed to overlie a subjacent stock". (p. 913). Within the stocks, at Llallagua, Potosi, Oruro, and Chorolque, there are "stockwork, disseminated, and breccia-filling cassiterite mineralisation" that Sillitoe *et al.* designate as porphyry tin deposits, and believe to have developed in the funnel-shaped stocks before tha lodes that intersect them. So in several respects the picture that emerges is similar to that encountered in Cornwall where some granitoid cusps containing, what I think are early swarms of greisen-bordered cassiterite-bearing veins, are flanked by stanniferous lodes.

In some tin provinces in orogenic regions the mineralisation is often closely associated with dykes of granitoid composition. This state of affairs occurs, for example, in Central Bolivia and in the southwest of England. In the latter province the dykes, which, with a few possible exceptions, pre-date the lodes, are often the close companions of the lodes. In such cases the lode may cling to the foot or hanging wall of the igneous body, may become rich where it intersects the dyke, may be deflected by the dyke, etc. The relationship has been dealt with by me in greater detail elsewhere (Hosking, 1962).

It seems that pre-lode dykes are most in evidence in those tin provinces which are characterised by the presence of high-level major granitoid intrusions with which the tin deposits are spatially and possibly genetically related. The emplacement of such pre-lode dykes must depend on the ability of the dyke-invading rock to be fractured at the appropriate time. Fracturing must depend, amongst other things, on the depth of emplacement of the associated major intrusives, the physical properties of the rocks involved, and the timing, intensity and duration of tectonic stress. In certain tin provinces, as in that of Central Bolivia, some of the dykes were, doubtless, associated with the development of the stratovolcanoes, and as such predate the emplacement of the funnel-shaped stocks, noted earlier. In other provinces, as in the Southwest of England, and as noted above, the granitoid dykes are, for the most part, pre-lode in age, whilst in other provinces one may find that the granitoid dykes are generally post-lode in age, as is the case, for example, at Pahang Consolidated Mine. In this mine the dykes are probably considerably younger than the associated tin lodes. If this is so it is another item in support of the view that once an area of limited extent is strongly mineralised as a result of multiple lode and/or vein development it remains structurally weak and is likely to be a preferred site for fracturing with which may be associated the emplacement of dykes and/or the modification of existing lodes by the invasion of late ore-forming agents, such as may have occurred at Geevor Mine, Cornwall, if one accepts the certain published radiometric dates (Darnley *et al.*, 1963 and Pockley, 1963).

The close association of tin, etc., mineralisation and dykes such as one finds in Cornwall is also paralleled by the association of tin mineralisation with certain members of the high-level plutono-volcanic (Kloosterman, 1967) ring complexes of the anorogenic regions of Nigeria and Rondonia. In Rondonia the tin mineralisation is generally associated with greisenised portions of what are largely medium- to coarse-grained, slightly porphyritic, pink, biotite granites, whose 'most characteristic feature --- is the euhedral quartz pseudomorphs after high temperature quartz" (Waghorn, 1973, p. 32). In the Odegi area of Nigeria the cassiterite/columbite is confined to a biotite granite which, unlike the neighbouring granites, is characterised by the presence of bipyramidal quartz whose presence in the overlying soil I found useful, years ago, in delineating the area to be mined. It is the presence of these quartz crystals that links them with the Cornish dykes and for that matter with the 'granite' ridge that extends from St Agnes via Cligga to Budnick in Cornwall and with which strong tin mineralisation is associated locally.

Finally, as noted earlier, the observed spatial relationship between tin deposits and granitoids and their volcanic equivalents is dependent on the level of emplacement of the igneous body and the level of development of the related mineral deposits, and on the amount of erosion of which the igneous bodies and mineral deposits have been subjected.

It seems certain that whatever the level of emplacement of the granitoid body, any associated tin mineralisation tends to be preferentially associated with the high spots. Tin deposits formed at the highest levels are those associated with volcanics as, for example, in Mexico and Central Bolivia. Tin deposits formed at the lowest levels are, in all probability, the pegmatites that are of particular economic importance in some of the anorogenic regions of Africa (for example, in Zaire, Nigeria and Rhodesia). Varlamoff (1975) was so convinced that the type of tin deposit depended on the level at which it developed that he proposed a classification of primary tin deposits that is based largely on this view. I think Varlamoff's view is broadly correct, and if it is so then one would expect few 'old' sub-volcanic tin deposits to occur and stanniferous pegmatites to be the last of the tin deposits in a given province to be eliminated by erosion.

Erosion by progressively changing the pattern of the tin deposits and their associated granitoids renders it progressively difficult to visualise the original pattern. If, for example, the dykes of the Southwest of England were associated with volcanic activity, then originally, as I have suggested earlier, there may have been sub-volcanic (including porphyry tin) deposits of the Bolivian type in the region which have since been destroyed by erosion. Finally, it is relevant to remark that although much is known about the spatial relationships between tin deposits and granitoids we are often unable to provide a satisfactory answer to the question as to why, in a given province, certain sites far out-shine the others in the strength of their mineralisation. Why, for example, is there no set of tin lodes in the East Tin Belt of Malaysia that compares in richness and strength with the Pahang Consolidated set? Why is the mineralisation at Kelapa Kampit tin mine (Belitung) so vastly superior to that of any other on the island?

The temporal aspect

This topic has already been part covered in earlier sections. The fact that tin deposits appear to be more abundant in and around the younger granitoids has already been mentioned, as has the possibility that the dominant types of tin deposit that developed during a given era depended on the geological age of the mineralisation. It has also been indicated that tin deposits are associated with the final intrusive phases of differentiated granitoid complexes. In addition it has also been noted that in a number of tin provinces, tin deposits of distinctly different geological ages occur, a fact that has been emphasised by Routhier and his colleagues (see Laboratoire de Geologie Appliquee, Universite de Paris, France, 1973) in support of his views of the consanguinity and inheritance of mineral deposits. It is relevant to mention here that when a tin province contains tin deposits of two distinctly different ages the earlier deposits may be distinctly different from the later. Thus, in Northern Nigeria cassiterite and tantalite-bearing pegmatites, of minor economic importance are scattered in the Older Granites (of late Cambrian to early Ordovician age?) whilst in the Younger Granites, of Jurassic age, cassiterite occurs generally in small veins and disseminations and it is the cassiterite (and columbite) released from these Younger Granites which constitute the values in the rich placers. In that part of the Tin Belt of Peninsular Thailand around Phuket, Phangnga and Takua Pa, lead and zinc mineralisation is associated with the porphyritic hornblende adamellites whilst the tin mineralisation is associated with younger two-mica granites (Garson, *et al.*, 1975). A further variation of the theme is recorded by Edwards and Gaskin (1949, p. 236) who write that "---- in the New England district of New South Wales and in the contiguous Stanthorpe district of Queensland, and again in the Blue Tier district of Tasmania, the "tin-granite" has invaded an earlier barren granite (granodiorite or adamellite)". Such examples, particularly, prompt the question 'from where did the tin in the deposits come?'. The question of the source of the tin in tin deposits generally is deferred until later.

Finally, although the concept of the deforming geosynclines is now replaced by plate tectonic concepts, the sequence in which ore deposits were thought to develop by Bilibin (1955) in what he regarded as a deforming geosyncline should not be discarded lightly, and must be taken into serious account by those seeking an adequate plate tectonics model for any tin province. Bilibin notes that tin is deposited first in association with ultra-acid potassic granites, alaskites, aplites and pegmatites and again with later granites and their hypabyssal and volcanic equivalents. He further notes that in the deposits related to the earlier group of igneous rocks tin may be associated with W, Mo, Bi, F, Li, Be, Ta and Nb, whilst in those deposits associated with the later group tin tends to occur with Pb, Zn, Ag, As and possibly W and Mo.

The chemical/mineralogical aspect and the source of the tin

In view of the fact that these topics have recently been reviewed in great detail by Hesp and Varlamoff (1977), Tischendorf (1977) and Stemprok (1977) I propose to treat the topics here in a summary manner.

Clearly not all granitoids have tin deposits closely associated with them, and following Tischendorf (1977) I shall term those granitoids with which tin deposits are spatially and perhaps gentically related "tin-specialised" granitoids. These rocks display certain geological, geochemical and petrographical peculiarities, and although they usually have higher than normal concentrations of tin this is not always so. They are post-tectonic, post-kinematic, and, in Tischendorf view, are amongst the last of the magmatic products of an intrusive cycle. These specialised granites (or stannigene granites) are the alaskites, aplites, two-mica granites and the leucogranites. Their precursors are generally adamellites or biotite granites, but occasionally quartz diorites and granodiorites.

In orogenic regions the tin-specialised granites occupy the uppermost portions of large plutons where they form stocks (cusps) and ridges. In anorogenic regions they may be associated with ring structures.

They tend to have a complex inner structure consisting of granitoids of varying type. Several workers (e.g. Tischendorf, 1977, p. 73) have established that there is an enrichment of granitophile elements (Sn, Li, Rb, G, F, Be and W) in the apices of these specialised granitoid intrusives and an impoverishment of intermediate and granitophobe elements (Ba, Sr, Ni, Cr, V).

That there are appreciable differences between the compositions of 'tin-granites' and normal granites, particularly in respect of their SiO_2, TiO_2, MgO and CaO content, is indicated when the compilations, made by Zhilinskii (1959), Sattran and Klominsky (1970) and Stemprok and Skvor (1974), of the average of the main components of the "tin-granites" are compared with the average composition of a normal granite according to Daly (1933) which appear in Table 4 (after Tischendorf, 1977, p. 50).

Furthermore, these highly specialised granitoids usually possess anomalous concentrations of certain trace elements. Essentially from a comprehensive study of the literature, Tischendorf (1977) provisionally arrives at the average content of certain trace elements in the specialised granites. These figures appear in Table 5 together with the range in the content of each of the trace elements in normal granites.

When one is concerned with the tin problem, the marked differences between the Sn and F contents of specialised granites, when compared with those of normal granites, are of considerable interest and importance. Within the granites tin is largely concentrated in biotite (to 400 ppm), amphibole (150 ppm), pyroxene (15 ppm), feldspars (10–50 ppm, important because of their abundance), shpene (3000 ppm), ilmenite (120 ppm), allanite (70 ppm), magnetite (50 ppm), zircon (75 ppm), protolithionite (500 ppm), tourmaline (1,500 ppm) and cassiterite. These figures,

TABLE 4

A COMPARISON OF THE AVERAGE COMPOSITION OF TIN GRANITES WITH THAT OF NORMAL GRANITE (AFTER TISCHENDORF, 1977.)

Components	Average of "tin granites" of the world according to			Average of normal granite
	Zhilinskii (1959)	Sattran-Klominsky (1970)	Stemprok-Skvor (1974)	Daly (1933)
	(185 samples)	(42 samples)	(368 samples)	
SiO_2	73.10	73.44	73.02	70.77
TiO_2	0.21	0.22	0.21	0.39
Al_2O_3	13.96	13.61	13.90	14.59
Fe_2O_3	0.91	0.92	0.78	1.58
FeO	1.44	1.38	1.34	1.79
MnO	0.06	0.06	0.05	0.12
MgO	0.55	0.47	0.52	0.89
CaO	1.21	1.30	1.24	2.01
Na_2O	3.01	3.13	3.28	3.52
K_2O	4.58	4.76	4.57	4.15

TABLE 5

THE CONTENT OF CERTAIN TRACE ELEMENTS IN SPECIALISED AND NORMAL GRANITES. (DATA AFTER TISCHENDORF, 1977)

Elements	Specialised granites	Normal granites
	Proposed average content (ppm)	Upper & Lower range of granites (ppm)
Sn	30 ± 15	1–8
Li	200 ± 100	37 ± 6–150
Rb	550 ± 200	270–130
W	7 ± 3	1–2.7
Mo	4 ± 2	< 1–2.5
Be	13 ± 6	2.6–8
F	3700 ± 1500	250–1500

provided by Tischendorf (1977), are probably, in some instances, seriously wide of the mark. Certain ilmenites from Malaysia, for example, that I have analyzed, contain up to 1500 ppm, whilst zircon from the same country may contain several per cent of tin, although it must be admitted that this high figure is largely due to minute inclusions of cassiterite.

Tischendorf (1977, p. 60) remarks that "early magmatic minerals are the main tin concentrators (sphene, hornblende, biotite) in the tin-poor granitoids ----. Late-magmatic minerals (protolithionite, cassiterite) are the main concentrators in tin-rich granitoids ----".

It is Tischendorf's (1977, p. 68–71) notion that a high concentration of volatiles, particularly fluorine, is necessary for the formation both of stannigene granites and of tin deposits, as they 'generate specific formation conditions, such as lowering of the freezing temperature, a decrease in the viscosity of the melt, and the commencement of late magmatic processes". He continues, "it seems, that the most important criterion in the formation of tin deposits related with granitoid intrusions is the high fluorine content and not the high content. Certain granites which are tin-specialised (*14 ppm) are not fluorine-specialised (700 ppm)". Elsewhere (p. 85) he makes the point that no tin deposits are found near granites with only 3 ppm Sn nor with only 800 ppm F, and he concludes that "a preconcentration of trace elements in the melt is necessary for the formation of ore deposits related to specialised granites". He does not commit himself to a definite view as to how the granites become tin-specialised but notes that some think it is a consequence of geochemical heredity whilst others such as Tauson (1976) hold that it is "caused by special physico-chemical conditions in the congealing rock and particularly by the presence of volatile constituents in the magma", so that perhaps as Anoshin *et al.* (1970) point out, 'potentially all granitic liquids are capable of forming associated ore deposits but their formation depends upon the content of volatiles in the melt and their separation from it".

So Tischendrof provides one view of the possible close relationship between granites and tin deposits, but it is not shared, at least in its entirety, by all.

It remains now to consider the source of the tin and the possible ways and means by which tin finds it ways into the ore deposit and is deposited there.

A consideration of the tin content in the major rock types, which has been noted earlier, indicates that practically any of them can provide the tin that reports in ore bodies: the problem is how can such a concentration be achieved, and this is a problem that has not been solved, although many solutions to it have been proposed. The tin may be derived from mantle or crustal sources or both, and good arguments have been advanced in support of all the proposed sources. Sillitoe, for example, as noted earlier, favours a mantle source for the tin that occurs in the long tin belt of South and Central America, but his view does not provide a happy solution to the problem of why tin deposits of distinctly different ages are found in this belt nor why a host of other heavy metals other than tin occurs in individual tin deposits there, and probably in quantity often outweighs the tin in the tin deposits. Because tin deposits of distinctly different ages are found in a number of the tin provinces of the World, I favour a crustal source and am very much a supporter of Routhier's view that late ore bodies often inherit some of their components, directly or indirectly, from earlier ore bodies. I also think that some of the hard-rock ore bodies, particularly some of those that are confined to a particular sedimentary or meta-sedimentary unit, and which have been generally regarded as owing their origin to the action of hydrothermal agents, containing tin, etc, genetically or apparently genetically related to neighbouring granites, may, in fact, have originally been stanniferous sediments that were subsequently modified by metamorphic and/or hydrothermal processes. The possibly that some ore deposits consist of material that has been collected by hot, deep, circulating ground- or -connate waters, as suggested by Boyle (1970), has many attractions but I find it difficult to believe that such waters would be so consituted that they would prove to be effective mobilisers of the tin occurring in the tin species or in trace amounts in other minerals.

Fundamentally, because of the spatial relationships between tin deposits and granitoids it was generally assumed that a close genetic relationship also existed

---

The 14 ppm is surely a mis-print in Tischendorf's paper.

between them. Such thinking, supported by field and laboratory evidence, culminated in Emmons' (1940, p. 185–194) view of the genesis of primary tin deposits, and about which I wrote (Hosking, 1965) as follows:- "Emmons suggested that during the crystallisation of a granitic magma "pools" of residuum collect under the "high spots" of the roof, and as this takes place so a vapour pressure develops which may reach such a magnitude that the overlying rocks are fractured, and the residuum, which is thus enabled to escape, wholly or in part, is instrumental in the formation of mineral deposits. If fracture takes place at a comparatively early stage, before the "granitic" components have been completely eliminated from the liquid phase, pegmatites develop: if fracture is delayed somewhat, the escaping products cause the generation of hydrothermal bodies, and if the vapour pressure never exceeds that of the confining rocks the residual liquid remains within the cooling igneous mass, where it may react with the granitic minerals effecting marked changes, and its heavy-metal ions may be incorporated in part, or entirely, in the new silicates: alternatively the heavy-metal ions may report in new accessory minerals which may be disseminated and/or locally concentrated in the igneous mass. Thus, in the last case, tin may be incorporated, in part, at least, in secondary micas; it might report as disseminated cassiterite grains (as, possibly, in parts of the Nigerian Plateau), or, perhaps, on comparatively rare occasions, as in the Potgietersrus tinfields of South Africa (Strauss, 1954, p. 141–147) it may segregate as cassiterite, together with species commonly found in hydrothermal lodes, in pipes just beneath the granite roof".

If Emmons' postulate is correct it is to be expected that in an area of limited extent major tin-bearing hydrothermal ore bodies and large pegmatites of the same age will tend to be mutually exclusive. This is, in fact, generally borne out by field observations: in the Wamba area of Northern Nigeria, in the Geomines district of Zaire, and in the Kamativi field of Rhodesia, where economically interesting hard-rock concentrations of cassiterite are virtually confined to the pegmatites: in Cornwall, on the other hand, numerous stanniferous lodes occur, but tin-bearing pegmatites have but seldom been recorded, and those that have been are small, of not more than slight economic importance and, in any event, many of them are feldspathic hydrothermal bodies, not pegmatites. In the Rooiberg field of South Africa tin only occurs in lodes and replacements.

"However, in order to stress the fact that the presence of important stanniferous pegmatites does not automatically exclude the presence of useful tin-bearing lodes of the same age it can be stated that in the Mumba-Numbi region of Kiva (Agassiz, 1954) a number of tin-bearing veins, of some importance, occur in the same general area as stanniferous pegmatites: the veins, however, by comparison with the Cornish lodes, are poorly mineralised".

Continuing, I suggested that Emmons' hydrothermal lodes commonly flank cusps capped by greisen-bordered tin veins. It seems reasonable to believe that each greisen-bordered vein-swarm developed from a pocket of residuum derived solely from the differentiation of the magma of the cusp. Later, as the batholith as a whole consolidated .... large 'pools' of residuum collected beneath the 'high-spots' of the roof, that is immediately below the cusps, which, provided they were "tapped" by the development of fractures, were capable of effecting the formation of much larger ore bodies than could possible develop from the small 'pools' derived from the limited magma of the cusps themselves". So, fundamentally, I then suggested what I now believe, and that is, that the deposits of greisen-bordered veins and the like that occur within, or in the vicinity of granitoid cusps, owe their development to the high-level, rather limited accumulations of mineralising agents that owed their existence to the crystallisation of the near-cusp parts, as opposed to the core, of the batholith. Later, the flanking major lodes were developed from comparatively deep-seated and large accumulations of residuum which stemmed from the crystallisation of the remainder of the magma and after, possibly, some of in had been released in such a manner as to allow the formation of volcanic bodies and/or dykes. It might also be added that the geometry of the primary zones in Cornwall is such that a deep source for the **lode-forming** agents must be postulated if it is held, as I do, that the zones owe their being primarily to the establishment of a temperature gradient along the passage-ways of the ascending mineralising agents.

I also noted in the paper referred to above (Hosking, 1965) that "in Bolivia the xenothermal lodes are commonly associated with cusps, or their equivalents the volcanic pipes, which sometimes contain in their uppermost horizons (as at Potosi: See Turneaure, 1960, p. 238–239) numerous mineralised veinlets which are approximately equivalent to the greisen-bordered veins of Cornwall" and I implied that this state of affairs could be accounted for in the way I have suggested above. I read with some satisfaction that the elegant studies of Sillitoe and his colleagues (1975) concerning these same Bolivian deposits led them to the recognition that there the stocks contain porphyry tin deposits which were followed, after an interval of time, by the generation of the lodes that are associated with the stocks. They state "that existence of magma chambers in depth as sources for hydrothermal fluids is strongly suggested (p. 274)" so they are at odds with my suggestion that the sources of the tin, etc., in greisen-bordered lodes and their broad equivalents, the porphyry tin deposits, were at relatively shallow depths. However, Grant *et al* (1976) when dealing with the same Bolivian topic, and while stating that "the mineralisation is the product of hydrothermal systems generated in the inner, deeper regions of terrestrial stratovolcanoes", later provide the following elaborations. They say "...... hydrothermal processes at the volcanic centres were intially controlled by the balance of confining lithostatic pressure and the pressure of the hydrous fluid residuum in the differentiated parts of the rhyodacite magma, leading to pervasive hydraulic fracturing, brecciation and alteration of which the early generation of cassiterite was an integral part. The upper levels of the mineralised volcanic structure appear to have stabilised while magmatic activity and hydrothermal generation at that level declined and the focus of generation to greater depths from which mineralisation was controlled by the interplay of tectonic stresses in the volcanic infrastructure and surrounding basement, and the build-up of hydrothermal fluid pressure in linear vein-fault systems".

"This concept of a bimodal style of mineralisation related to a retreating hydrothermal focus can lead to a clearer understanding of the xenothermal ... type of mineral and temperature zonation in subvolcanic systems".

Stemprok (1977, p. 144) does not think that the "granites are the direct carriers of the ore deposition to the upper parts of the earth's crust", but that "they are only the places where the import of solutions which gave rise to the ore deposits occurred", and that "the ore specialisation takes place at a late stage by the inflow of postmagmatic solutions which affected the rocks where these granites occurred". He further states (p. 155) "that the solutions which gave rise to the tin and tungsten deposits in the Krusnehory-Ergebirge are not derived from the same granite but came from a deep source in the earth's crust". "The formation of the deposits occurred along the contact of the large batholiths which were emplaced before the inflow of the solutions of deep-seated origin".

Others also hold that the tin found in the tin deposits is of deep-seated origin. Sainsbury and Hamilton (1968), for example, believe that tin mineralisation occurred well after the granites with which it is associated, and that the ore-forming agents migrated upwards to the seats of deposition via the post-granitic intrusion major faults which, they think, are much in evidence in tin-fields. Verschure and Bon (1972) are of the view that the tin in the plutono-volcanic complexes of anorogenic regions, such as Rondonia and Nigeria, may have been derived from granitic magmas which had inherited the tin in a volatile fraction from the basaltic magmas that had generated the granitic magmas by partial crustal fusion.

By studying the fluid inclusions in suitable minerals from hard-rock tin deposits, evidence has been obtained that it is probable that the cassiterite and some of its companion minerals were deposited from aqueous solutions characterised by the presence of sodium ions together with chloride and fluoride ions and/or chloro- and fluoro-complex ions. Many (Hesp and Varlamoff, 1977, p. 25) believe that "tin is transported as a volatile halide in the relatively deep regions (around 300 km)" and Hesp and Rigby (1972) have established, by experimental means, that in a dry environment Cl transports tin more effectively than F, whereas in aqueous solutions the reverse holds. It is further envisaged by some (Hesp and Varlamoff, 1977, p. 25) that these ascending tin/halide fluids "react with meteoric hypersaline brines in higher regions and alkaline aqueous solutions carry the tin in complex form as sodium fluoro-stannate, $Na_2[Sn(OH,F)_6]$. ----------- A change in pH (caused by reaction with country rocks) and decreasing temperature are the main reasons of the precipitation of cassiterite, mostly in the temperature range 300–350 °C".

Barsukov (1957) is of the opinion that the tin in the tin deposits is essentially derived from the biotites of the granitoids from which it is leached by solutions rich in sodium and fluoride ions and from which it is transported as sodium fluoro-stannate. He claims that the leached zone below the tin deposits is strongly albitised. Experimental work of Hesp and Rigby (1972) has caused them to doubt the validity of the leaching hypothesis, whilst studies by Ontoev (1974) have led him to the conclusion that microclinized and albitised granites, that were supposed to have been so altered by processes involving the leaching of tin are, in fact, 3–4 times richer in the element than the unaltered granite. I found that the conversion of biotite to muscovite in the Carnmenellis granite (Cornwall) was not accompanied by a loss of tin, but that when the greisenised granite of the Cameron Quarry, St Agnes (Cornwall) was silicified the element in question was mobilised. So I concluded that tin might be derived from biotite by a 2-stage process, which first converted the biotite to muscovite, without the loss of tin, and which then destroyed the muscovite, liberated the tin (and certain other elements) and silicified the rock (Hosking, 1965).

Whilst experimental work and observations of the type noted above give strong reasons for supposing that commonly fluorine plays a major rôle in the transportation and deposition of tin, particularly as cassiterite, and whilst this view is supported by the fact that commonly within and adjacent to tin deposits minerals containing essential fluorine, or substantial trace-amounts of the element, are to be found, I think there may well be occasions when the rôle of fluorine is taken over by another element. Thus, for example, as Mulligan (1975, p. 59) remarks in his comprehensive review of the transport and deposition of tin "transport as a chloride seems particularly appropriate for tin in presumably syngenetic volcanogenic massive sulphide deposits ....". Smith (1947) having noted the presence of sulphide-rich tin deposits that apparently lacked fluorine (and boron) minerals, investigated the means by which the tin might have been transported and deposited under such circumstances. The results of his experimental work led him to conclude that in such an environment the tin might have been transported in a system containing thiostannate (SnS^{-4}) and stannate ($SnO_4{}^{-4}$) ions in equilibrium, and that from this system cassiterite might be expected to be deposited early and tin-bearing sulphides late.

One must conclude this section by saying that we are still uncertain as to how the tin and some of the related elements were transported to the sites of ore-deposit development, nor do we know the reactions which were involved during the deposition of the tin minerals and those species that commonly accompany them. We do not know why such elements as Mo, W, Fe, Cu, Bi, As, Pb, and Zn are common associates of tin in the primary deposits, and why there is so little variation in the order of deposition of the minerals in such deposits.

In spite of what has been written above many aspects of our views of the genesis of tin and other deposits may have to be radically revised if, as Cann (1970) holds, 'wet granite magma cannot rise far from its place of formation, and only dry granite magma can be erupted as a liquid'. This means that high level granitoid intrusives (and effusives) might not contain sufficient water to provide a residuum which, by one means or another, that have been discussed earlier, may lead to the generation of ore-deposits. So one might have to fall back on either a theory of ore-genesis of the Boyle (1970) and Henley (1973) type and/or on one of the Stemprok (1977) type. Briefly, Henley (Fig. 7) believes that the ascending magma generates, at a high level, convection currents within the saturated rocks which it is invading. The convected liquids scavenge metals, etc., from the country rocks and deposit them ahead of the advancing magma. At a later date, when the magma consolidates, it will fracture and then the solutions will be free to leach tin, etc., from the igneous body and these metals will then be deposited within and adjacent to the granitoid.

If Henley's views are correct one should commonly expect to find copper, lead, zinc, etc., deposits in the granitoid-invaded country rock that are earlier than the tin(tungsten) deposits, but this is not the case. Furthermore, I find it difficult to believe that if a fluoride-rich solution is, indeed, needed to leach tin from the components of the granitoid, that the convecting solution would be of this nature.

If one adopts Henley's model then one might say in defence of it, in addition of what Henley himself has said, that differences in the nature of the mineralisation in and around granitoids may also depend on the concentrations and modes of occurrence of the ore-elements in the granitoid-invaded rock, the degree of permeability of the latter, the concentration of tin, etc., in the granitoid, and the size, shape and temperature of the latter when it reached a high level.

Stemprok's view that the mineralising agents ascended from a deep source or sources and entered the already emplaced granitoid, modifying it and generating ore-deposits, needs little modification to conform with Cann's view. In addition, Stemprok's deep-source mineralising agents may be fluoride-rich and capable, if necessary, of leaching tin from the silicates of the granitoid, although they might be conceived as transporting the tin and associated elements directly from the deep parent source. Cann (p. 338) points out "in general terms, the higher a granite rises, the deeper it must have been formed ...." so that it seems reasonable to think that the magma of such high-level granites may have developed at the base of the crust or possibly the upper mantle, whereas in part the mineralising agents may well have developed in the manner postulated by Henley, and I can see no reason why the views of Henley and

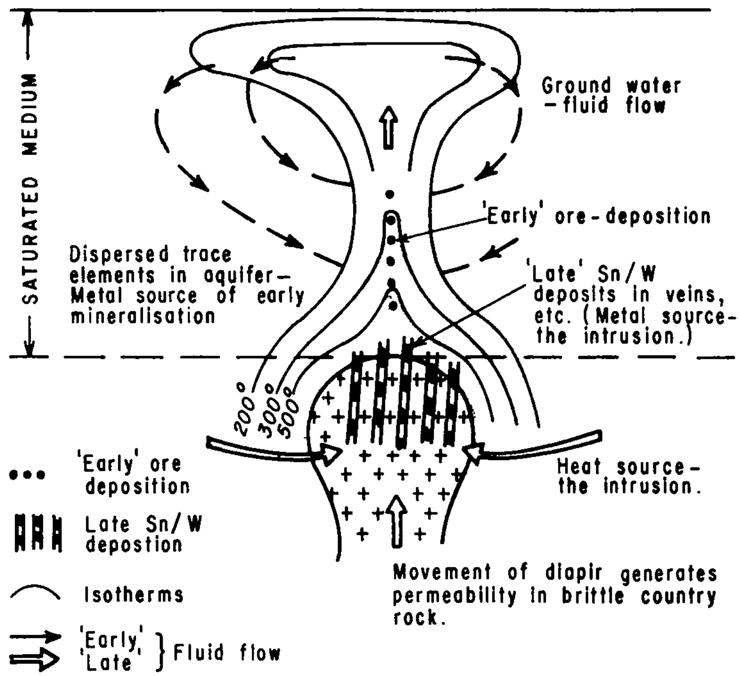


Fig. 7. Ore genesis within a geothermal convective system. (Based on Henley, 1973).
When diapir cools and solidifies it will fracture and Sn, W, etc., may be leached from it. The Sn, W, etc. may be deposited in and around the granitoid and the latter may be altered.
Questions: 1. Is Henley's fluid likely to be capable of leaching tin from a granitoid?
2. Is pre-tin mineralisation common around cusps bearing tin deposits? Does it occur, for example, in Cornwall?

Stemprok should not be incorporated into a single model. This combined basic model is for me the most satisfactory one, **if those erected more-or-less according to the Emmons' model have to be abandoned** although I think that in due course the Emmons-derived models will be shown to be sound. Finally, I am not adverse to the view that during tin epochs some of the tin that finds its way into ore-deposits may be derived from the mantle, but for reasons that I have noted earlier I think that most of it is obtained from crustal sources.

E. Tin distribution patterns in the surface and near-surface environments in tin provinces

The nature and development of tin distribution patterns in the surface and near-surface environment of tin provinces is a topic of such dimensions that it can only be dealt with in a very broad way in this paper.

Clearly, the development of these patterns depends on many factors, but fundamentally what makes these patterns different (at least locally) from those found in non-stanniferous regions is the presence of locally high concentrations of tin in the form of hard-rock tin deposits. Ultimately denudation uncovers such deposits and their components will be subject to disintegration and decomposition, and there will be dispersion of the products into such units as neighbouring decomposed rock, soil, plants, animals, air, drainage system, suitably placed unconsolidated deposits, such as beach sands, and the sea. Locally some of the unitially dispersed components may become reconcentrated. This is most likely to happen to the dense minerals that have been liberated and that are inert, or reasonably so, in the superficial environment. Such a mineral is cassiterite, and some of the species that may be concentrated with it, in some but not necessarily all of the placers associated with a given primary source, are tantalite/columbite, wolframite (but only in placers close to the primary source), scheelite, gold, which are derived from the tin deposit and/or from some other type of deposit closely associated with it, together with zircon, ilmenite, monazite and xenotime if the host rock is a granitoid, or if there is any other granitoid present that can contribute to the site of cassiterite accumulation.

So broadly speaking the partial or complete destruction of stanniferous deposits may lead to the generation of secondary accumulations of cassiterite of real or possible economic importance. These are termed placers and they are classified pictorially in figure 8. In addition, anomalous concentrations of tin, of no economic value, may develop, particularly in the soils associated with the primary source and in the sediments of streams draining the primary source area. These anomalous concentrations of tin are often accompanied by anomalous concentrations of other elements that have migrated from the primary deposit during its destruction by superficial agents. The establishment and analyses of these soil and sediment patterns constitute, in my opinion, the most effective of the geochemical methods which have been employed by those searching for tin deposits.

Of the many factors that determine the nature of the 'surface' tin distribution patterns on the regional and/or the local scale, those which are noted below, and generally briefly commented on, appear to be the most important:-

i. **The distribution patterns of the hard-rock tin deposits.**

ii. **The geological and climatic history, ideally from the time the primary orebodies were formed, but especially from the time they began to be uncovered.**

One might cite many examples in support of the importance of this second factor but the following will suffice. In the Southeast Asian Tin Belt it is probably that the major fluctuations in sea-level during Pleistocene times, due to the removal of sea-water as ice and the subsequent return of water to the oceans as the ice melted, played a major part in developing the present placer patterns by inducing rejuvenation of the rivers and rapid valley erosion, followed by transgression of the land by the sea which resulted in re-working of placers previously developed on land.

The Nigerian pattern is to no small degree dependent on the fact that some of the valleys containing stanniferous placers were infilled with basalt and that a new drainage systems developed.

As Varlamoff (1975) has pointed out, the climatic conditions to which a hard-rock tin deposit is exposed largely determines how rapidly and effectively its cassiterite can be concentrated in placer deposits. It is concluded that a tropical climate is the optimum one as it provides the best conditions for the destruction of the primary body, for the rapid transportation of the cassiterite and for its subsequent concentration, particularly in the drainage system.

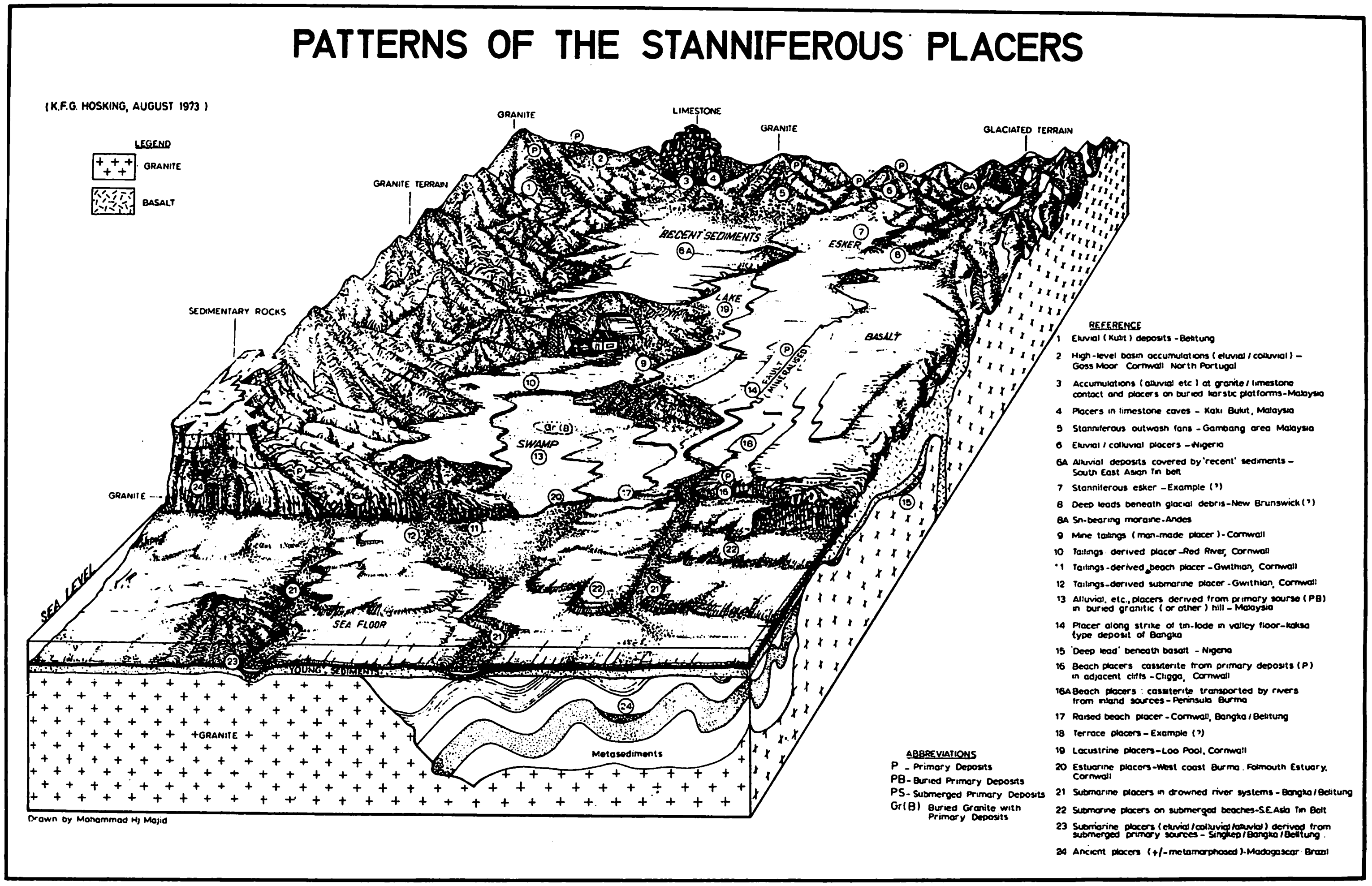


Fig. 8. Patterns of the stanniferous placers. (After Hosking, 1974).

iii. *The nature of the hard-rock tin deposits*

In a climate that is not an arid one the following ore-body characteristics help to determine the rate at which cassiterite can be released from it:-

The species present. The textural pattern. The ratio of species that are decomposed readily (especially the sulphides) to the inert ones (particularly quartz and cassiterite). The ease with which gases and liquids can move into and out of the body. The size distribution ranges of the primary and secondary insolubles.

That the above factors are important is obvious when one considers that whatever the climatic conditions a quartz-cassiterite lode can only be destroyed, and often with difficulty, by physical means, whereas should the lode also contain species (particularly sulphides and carbonates) that can readily be decomposed by supergene agents, under ideal conditions, some, and eventually all of the lode may be converted to such a weak structure that the further destruction of the weakened part may be readily effected by comparatively mild physical forces. The ease with which decomposition can be achieved must depend on the extend to which the unstable species can be reached by the solvents, and this depends on the effectiveness of the channelways both within the body and in the adjacent wallrocks. It also depends to what extent the unstable minerals are guarded against attack by the inert species. The extent to which free cassiterite is ultimately released from the orebody depends on how and with what minerals it is closely associated in the orebody. Should most of the cassiterite be surrounded by unstable species much of the tin species is likely to be liberated in a free state, but should it be intimately related to, say, quartz and tourmaline, and particularly if the cassiterite occurs as small crystals, then a high proportion of cassiterite-containing composite grains is to be expected.

iv. *The geological character of the area embracing the parent source of the tin and the associated drainage systems.*

The nature, relative amounts and distribution of the major lithologic units, together with climatic factors and the forces leading to uplift or subsidence, largely determine the topography of a given region. The relationships between topography and stanniferous placers are legion, and space allows only a few to be mentioned here. Variations in the gradient of a river may be one of the major factors in determining the optimum sites for concentration of cassiterite in the fluviatile deposits. This has been very well demonstrated in Nigeria by Mackay et al. (1949, p. 16–17). The karstic 'limestone' platforms with their markedly enlarged joints and pot-holes were major collecting and concentrating units during the development of the stanniferous placers of Malaysia, but particularly in the Kinta and Selangor fields, Hard-rock tin deposits, in hills, in any given climatic condition, but particularly in those regions that are subject to a tropical climate, are much more readily destroyed than low-lying similar deposits. On a hill the water table is deeper below the surface than on the lowland, hence if the lodes contain unstable species the one on the hill is likely to be oxidised and weakened to a considerably greater depth than one of the lowland. Indeed, in Malaysia the water table on the lowlands is commonly so high that the sulphides in many of the lodes there have suffered little or no attack by supergene agencies. On the hillside sheet flow may, on occasion, readily transport portions of the oxidised ore to lower horizons, whilst landslides in a tropical country with an immature topography may be the means of transporting vast amounts of hillside ore to a lower horizon in a most spectacular way. Landslides and rock falls of one sort or another, and in a variety of different climates, are, I think, important means by which stanniferous bodies, not well-endowed with unstable minerals, such as swarms of greisen-bordered veins, can be reduced to fragments of such a size that they can be further reduced, without undue difficulty, by river or wave action. Collapse of portions of the cliffs at Cligga (Cornwall), which contain greisen-bordered stanniferous veins, have yielded fragments which are being further milled by the waves with the consequent release of cassiterite (and wolframite). Finally, in hot climates, whether they be wet or dry, ore bodies exposed on the hillsides may be weakened by suffering granular disintegration, or something akin to it, as a result of stresses set up due to rapid heating and cooling and as a result of the unequal expansions and contractions of the various components. In tropical regions the rapid cooling is effected by the frequent heavy rains falling on the hot rocks.

v. *Man*

As a result of the exploitation of tin deposits and the use of the metal in question, man has grossly distorted the natural 'surface' tin distribution pattern and is continuing to do so. In effect, what he has done, and is doing, is to take the tin from the comparatively small sites where it occurs in marked concentration (due to natural causes) and to disperse it over both large and small areas. Generally speaking, his earlier exploitations have increased, by contamination of one sort or another, the difficulties encountered when prospecting in "old" mining fields, and particularly when geochemical methods are used (Hosking, 1971b). Mine dumps may contaminate the soil and local drainage systems, and roads and hedges constructed from mine waste rock may do likewise. Concentrations of tin, that may mislead the unwary geochemist, may occur in the vicinity of active and abandoned mine workings, along paths frequently used by miners; along the lines of mineral railways; beneath overhead ore-transporting systems, and in the vicinity of active or abandoned tin smelters. Given time, Nature may so camouflage such places that these "traps" for the unwary searcher for tin deposits are only sprung by library research and the most careful and critical examination of the ground.

In tin mining regions some of the rivers are polluted by tailings. Such pollution need not, of necessity, be confined to rivers draining the locations of mines. In Cornwall, at any rate, some rivers in non-mineralised areas have been polluted with tin because, in the past, customs mills and smelters had been erected on their banks to take advantage of an abundant water supply, etc. (Hosking, 1971b).

Finally, Nature may so rework mine tailings that placers of economic interest accrue. Thus, in West Cornwall, the Red River, for generations, has carried tin tailings to the Gwithian area of St. Ives Bay. There the sea produced from them both offshore and onshore placers that have been worked, the latter, on occasion, at a profit (Hosking and Ong, 1963–64).

CONCLUSIONS

In this 'background' paper I have tried to indicate in a general way what we know and what we do not know about tin distribution patterns both large and small. I have deliberately drawn heavily upon my own experiences, believing that by so doing I can best make a useful contribution. I have endeavoured to highlight certain topics that I believe to be of particular importance now, and other, that although important, have been somewhat neglected in recent tin literature.

It is evident that the nature of the various tin distribution patterns is now much more clearly defined than it was, say, a decade ago, and this has served to facilitate the search for tin deposits and their evaluation and exploitation. It is with the establishment and analysis of tin distribution patterns that the applied geologist, mining engineer and mineral dresser are primarily concerned.

In spite of the numerous ancient and modern researches relating to the natural occurrences of this maverick element tin, the subject still provides many unsolved, or only partially solved, problems. We still know all too little as to why individual primary deposits are where they are. We are uncertain of the source or sources of the tin that occurs in the primary deposits, nor do we know the sources of the metals that commonly accompany the tin. We do not know how the tin was transported to the site of primary deposition, nor are we sure of the chemical reactions of its deposition. The list of uncertainities and unknowns could be increased. Still, it is the existence of so many unsolved problems that makes the study of the tin deposits so attractive and so rewarding.

REFERENCES

ADAM, J.W.H., 1960. On the geology of the primary tin deposits in the sedimentary formation of Billion. *Geologie Mijnb.*, 39, 405–426.

AGASSIZ, J., 1954. *Geologie et pegmatites stanniferes de la region Mumba-Numbi, Kivu (Congo Belge)*. Comite National du Kivu. Bruxelles.

ANOSHIN, G.H. *et al.*, 1970. About the ore content in granitoidic magmas. *Geokh. krit. pot. rudon. granitoidov. Inst. geokh. sib. otd.*, Irkutsk, 189–215 (In Russian)

ARANYAKANON, P., 1970. Tin deposits in Thailand. In *'A second technical conference on tin'. Bangkok, 1969.* I.T.C., 83–102.

BARSUKOV, V.L., 1957. On the geochemistry of tin. *Geochemistry*, 1, 41–45.

BATEMAN, A.M., 1950. *Economic mineral deposits.* Wiley and Sons, Inc., N. York, 916 p.

BILIBIN, Y.A., 1955 *Metallogenetic provinces and epochs.* Gosgeoltekhizdat, Moscow. (In Russian).

BOTH, R.A. and Williams, K.L., 1968. Mineralogical zoning in the lead-zinc ores of the Zeehan field, Tasmania. *J. Geol. Soc. Australia*, 15, 121–137 and 217–244.

BOWDEN, P. and van Breeman, O., 1972. Isotopic and chemical studies on younger granites from northern Nigeria. *Inc.* Dessauvagie, T.F.J. and Whiteman, A.J., Eds., "African Geology" University of Ibadan, Nigeria, 105–120.

BOYLE, R.W., 1969. Elemental associations in mineral deposits and indicator elements of interest in geochemical prospecting. *Geol. Surv. Canada, Pap.* 68–58.

BOYLE, R.W., 1970. The source of metals and gangue elements in hydrothermal deposits. *In* Pouba, Z. and Stemprok, Meds., "*Problems of hydrothermal ore deposition*," IAGOD Symposium, Scotland, 3–6.

BRADFORD, E.F., 1961. The occurrence of tin and tungsten in Malaya. *Proc. 9th. Pacif. Sci. Congr.*, 12, 378–398.

BRADSHAW, P.M.D. and Stoyel, A.J., 1968. Exploration for blind orebodies in southwest England by the use of geochemistry and fluid inclusions. *Trans. Instn. Min. Metall.*, 77, B144–152.

BULLARD, E., Everett, J.E. and Gilbert Smith, A., 1965. The fit of the continents around the Atlantic. *Phil. Trans. Roy. Soc.*, 258, 41–51.

BURNHAM, C.W., 1959. Metallogenic provinces of the Southwestern United States and Northern Mexico *Bull. New Mexico Inst. Mines and Techn.*, 59, 1–76.

CANN, J.R., 1970. Upward movement of granitic magma. *Geol. Mag.*, 107, 335–340.

CHURCHILL, W.L.S., 1939 (22nd Feb.) Speech, House of Commons. London.

CLARK, A.H. 1969. A second occurrence of berndtite: Lagares-do-Estanho, Queiriga, Viseu, Portugal. *N. Jb. Miner.*, 426–430.

COLLINS, J.H., 1881. Note on the occurrences of stanniferous deers' horns in the tin-gravels of Cornwall. *Trans. R. geol. Soc. Cornwall,* 10, 1–3.

COLLINS, J.H., 1882. On some Cornish tin-stones and tin capels. *Min. Soc.*, 4, 1–34.

DALY, R.A., 1933. *Igneous rocks and the depths of the Earth.* N. York.

DARNLEY, A.G., English, T.H., Sprake, O. and Preece, E.R., 1963. Additional uranium-lead ages from south-west England(Abs.) *Notice 125 Min. Soc., Lond.*

DAVISON, E.H., 1919. On the mode of occurrence of cassiterite in some Cornish rocks and veinstones. *Trans. R. geol. Soc. Cornwall,* 15, 279–285.

DAVISON, E.H., 1925. A study of the Cornish granite, its variation and its relation, if any, with the occurrence of tin and other metallic ores. *Trans. R. geol. Soc. Cornwall,* 15, 501–508.

DERRY, D.R., 1930. Tin-bearing pegmatites in Eastern Manitoba. *Econ. Geol.*, 25, 145–159.

DINES, H.G., 1934. The lateral extent of the ore-shoots in the primary depth zones of Cornwall. *Trans. R. geol. Soc. Cornwall,* 16, 279–296.

DMITRIEV, L., Barsukov, V., and Udintsev, G., 1971. Rift-zones of the ocean and the problem of ore-formation. *Society of Mining Geologists of Japan,* No. 3, 65–69.

DUDYKINA, A.S., 1959. Paragenetic associations of element-admixtures in cassiterites of different genetic types of tin-ore deposits. *Akad. Nauk SSSR, Inst. geol. rudnykh mestorozhd., petrog., mineral., i geokhim.*, 28, 111–121.

DMITRIEV, Barsukov, V. and Udintsev, G., 1971. Rift zones of the ocean and the problem of ore-formation. *In* Takeuchi, Y., Ed., "*Papers and proceedings of the International Association on the Genesis of Ore Deposits Tokyo-Kyoto Meetings, 27 Aug–2 Sept 1970*" Soc. Min. Geologists Japan Special Issue No. 3, 65–69.

DURASOVA, N.A., 1967. Some problems of the geochemistry of tin. *Geokhiminya,* 7, 802–812. (Translation: in *Geochem. Intern.*, 4, pt. 4, 1967).

EDWARDS, A.B. and Baker, G., 1954. The oxidation of stannite ore at the Sardine Tin Mine, Queensland. *Proc. Australian Inst. Min. Metall.*, 172, 65–79.

EDWARDS, A.B. and Gaskin, A.J., 1949. Ore and granitization. *Econ. Egol.*, 44, 234–241.

EMMONS, W.H., 1940. *The principles of economic geology.* McGraw-Hill, N. York.

FICK, L.J., 1960. The geology of the tin pegmatites of Kamativi, Southern Rhodesia. *Geologie Mijnb,* 472–491.

FLINTER, B.H., 1960. The effects of heat, hydrochloric acid and lead chloride on some Malayan mineral grains. *Overseas Geol. Miner. Resour.*, 8, 54–56.

GARNETT, R.H.T., 1966. Relationship between tin content and structure of lodes at Geevor mine, Cornwall. *Trans. Inst. Min. Metall.*, 75, B1–22.

GARSON, M.S., and others. 1975. The geology of the tin belt in Peninsular Thailand around Phuket, Phangnga and Takua Pa. *Overseas Mem. Inst. Geol. Sci.*, 1, 112 p.

GERASIMOVSKIY, V.I. and Borisenok, L.A. 1968. Geochemistry of tin in nepheline syenites. *Geochem. Int.*, 675–678. (Translation of *Geokhimiya,* no. 7, 713–785, 1968.)

GILMOUR, P., 1962. Notes on a non-genetic classification of copper deposits. *Econ. Geol.*, 57, 450–455.

GOLDSCHMIDT, V.M., 1937. The principles of distribution of chemical elements in minerals and rocks. *J. Chem. Soc.*, 655–673.

GOLDSCHMIDT, V.M., 1954. *Geochemistry*. Oxford, Clarendon Press. 730 p.

GRANT, J.N., Halls C., Avila, W. and Avila, G., 1976(?). Igneous geology and evolution of hydrothermal systems in some sub-volcanic tin deposits of Bolivia. (In press)

GRUBB, P.L.C. and Hannaford, P., 1966. Magnetism in cassiterite. *Mineral Deposita*, 2, 148–171.

HALLS, C. 1974. Tin and plate tectonics. *The Indian and Eastern Engineer*, 116, 493–494.

HAMAGUCHI, H., Rokuro, K., Onuma, N., Kawabuchi, K., Mitsubayashi, T., and Hosohara, K., 1964. The geochemistry of tin. *Geochim. Cosmochim. Acta*, 28, 1039–1953.

HAWKES, H.E. and Webb, J.S., 1962. *Geochemistry in mineral exploration*. Harper and Row, N. York. 415 p.

HAWKES, J.R., 1974. Volcanism and metallogenesis: the tin province of South-west England. *Bull. Volcanologique*, 38–4, 1125–1146.

HENLEY, R.W. 1971. See 'Report of discussion and contributed remarks on a number of papers'. *Trans. Instn. Min. Metall.*, 80, B59.

HENLEY, R.W., 1973. Some fluid dynamics and ore genesis. *Trans. Instn. Min. Metall.*, 82, B1–B8.

HESP, W.R. and Rigby, D., 1972. The transport of tin in acid igneous rocks. *Pacific Geol.*, 4, 135–152.

HESP, W.R. and Varlamoff, N., 1977. Temporal and spatial relations between the formation of acid magmatic rocks and deposits. *Metallization associated with acid magmatism*, 2, Geol. Surv. Prague, Czechoslovakia, 23–37.

HOLMES, A., 1965 *Principles of physical geology*. Nelson. 1288 p.

HORN, M.K. and Adams, J.A.S. 1966. Computer-derived geochemical balances and element abundance. *Geochim. Cosmochim. Acta*, 30, 279–297.

HOSKING, K.F.G., 1953–54. The vein system of St. Michael's Mount, Cornwall. *Trans. R. geol. Soc. Cornwall*, 18, 526–534.

HOSKING, K.F.G., 1954. The pegmatites of Trolvis Quarry, Carnmenellis, Cornwall. *Geol. Mag.*, 273–285.

HOSKING, K.F.G., 1957–58. A re-examination of an alleged stanniferous deer's horn from the Cornish tin-bearing alluvials. *Trans. R. geol. Soc. Cornwall*, 19, 154–161.

HOSKING, K.F.G., 1962. The relationship between the primary mineralisation and the structure of South-west England. In Coe, K., Ed., '*Some aspects of the Variscan Fold Belt*' Manchester Univ. Press, 135–153.

HOSKING, K.F.G., 1963. Geology, mineralogy and paragenesis of the Mount Pleasant Tin Deposits, *Can. Mining J., 84*, 95–102.

HOSKING, K.F.G., 1964. Permo-Carboniferous and later primary mineralisation of Cornwall and South-west Devon. In Hosking, K.F.G. and Shrimpton, G.J., Eds., '*Present views on some aspects of the geology of Cornwall and Devon*'. Blackford Ltd., Truro, 201–245.

HOSKING, K.F.G., 1965. The search for tin. *Mining Mag.*, 113, 261–273, 368–383, 448–461.

HOSKING, K.F.G., 1967. The nature and significance of certain 'late' veins of southwest Cornwall which are characterised by the presence of potash feldspar. *Camborne School of Mines Mag.*, 67, 42–59.

HOSKING, K.F.G., 1968. The relationship between primary tin deposits and granitic rocks. *A technical conference on tin. London, 1968.*, I.T.C., 269–306.

HOSKING, K.F.G., 1970a. The nature of the primary tin ores of the Southwest of England. *A second tech. Conference on tin, Bangkok, 1969*. I.T.C., 1155–1243.

HOSKING, K.F.G., 1970b. Aspects of the geology of the tin fields of Southeast Asia. *A second tech. Conference on tin, Bangkok, 1969*. I.T.C., 39–79.

HOSKING, K.F.G., 1971a. The role of impounding structures in the localisation of primary ore deposits in South-east Asia. *Malayan Scientist*, 6, 54–65.

HOSKING, K.F.G., 1971b Problems associated with the application of geochemical methods of exploration in Cornwall, England. *Proc. 3rd Int. Geochem. Exploration Symposium, Toronto, 1970*. Canadian Inst. Min. Metall, Special Vol. 11, 176–189.

HOSKING, K.F.G., 1973. Primary mineral deposits. *In* Gobbett, D.J. and Hutchison, C.S., Eds., Chap. 11 of '*Geology of the Malay Peninsula*', Wiley-Interscience, N. York, 335–390.

HOSKING, K.F.G., 1974. The search for deposits from which tin can be profitably recovered now and in the forseeable future. *Fourth world conference on tin, Kuala Lumpur, 1974*. I.T.C., 21–76.

HOSKING, K.F.G., 1977. Known relationships between the 'hard-rock' tin deposits and the granites of Southeast Asia. *Bull. Geol. Soc. Malaysia*, 9, 141–157.

HOSKING, K.F.G., and Ong, P.M., 1963–64. The distribution of tin and certain other "heavy" metals in the superficial portions of the Gwithian/Hayle beach of West. Cornwall. *Trans R. geol. Soc. Cornwall, 19*, 351–390.

HUTCHISON, C.S., 1973. Tectonic evolution of Sundaland: a Phanerozoic synthesis. *Bull. Geol. Soc. Malaysia*, 6, 61–86.

IVASHOV, P.V. and Bardyuk, 1967. Biogeochemical investigations at the far eastern tin deposits (Abs.) *Geochem. Int.*, 4, p. 158.

JACKSON, N.J., 1975. The Levant Mine carbona. *Proc. Ussher Soc.*, 3, 220–225.

JACKSON, N.J. and Rankin, A.H., 1976. Fluid inclusion studies at St. Michael's Mount. *Proc. Ussher Soc.*, 3, 430–434.

JONES, M.T., Reed, B.L., Doe, B.R. and Lanphere, M.A., 1977. Age of tin mineralization and plumbotectonics, Belitung, Indonesia. *Econ. Geol.*, 72, 745–752.

JONES, M.P., 1967. Some impressions of the tin mining industry of Southeast Asia. *Trans. Instn. Min. Metall., Section A*, 76, A1–A13.

JONES, W.R., 1925. *Tin fields of the world*. Lond. 423 p.

KATILI, J.A., 1973. Plate tectonics and its significance in the search for minerals deposits in Western Indonesia. *United Nations ECAFE, CCOP Tech. Bull.*, 7, 23–37.

KELLY, W.C. and Turneaure, F.S., 1970. Mineralogy, paragenesis and geothermometry of the tin and tungsten deposits of the Eastern Andes, Bolivia. *Econ. Geol.*, 65, 609–680.

KHOO, H.P., 1969. *Mineralisation at Pelepah Kanan, Kota Tinggi, Johore, West Malaysia*. Unpubl. B. Sc. (Hons) Thesis, Dept. of Geology, University of Malaya.

KLOOSTERMAN, J.B. 1967. A tin province of the Nigerian type in southern Amazonia. *A technical conference on tin London, 1967*. 381–400.

KOSTOV, I., 1968. Notation and genetic significance of crystal habits. *In Papers and Proceedings of the 5th general meeting of the International Mineral Assoc. at Cambridge, England. (Mineral Soc.), London*, 100–109.

LABORATOIRE de Geologie Appliquee, Universite de Paris, France, 1973. Some major concepts of metallogeny. *Mineral. Deposita (Berl.)*, 8, 237–258.

LEUBE, A. and Stumpfl, E.F., 1963. The Rooiberg and Leeupoort Tin Mines, Transvaal, South Africa. *Econ. Geol.*, 58, 391–418 and 527–557.

MACKAY, R.A.. 1925. The influence of superimposed strata on the formation of certain lead-zinc ores. *Trans. Instn. Min. Metall.* 33.

MACKAY, R.A., 1946. The control of impounding structures in ore deposition. *Econ. Geol.*, 41.

MACKAY, R.A., 1948. Localisation of ore in impounding structures. *Mining Mag.*, 73–84.

MACKAY, R.A., Greenwood, R. and Rockingham, J.E., 1949. The geology of the Plateau tinfields—resurvey 1945–48. *Bull. Geol. Surv. Nigeria.*, 19.

MITCHELL, A.H.G., 1973. Metallogenic belts and angle of dip of Benioff zones. *Nature Phys.*, 245, 49–52.

MITCHELL, A.H.G., and Garson, M.S., 1976. Mineralization at plate boundaries. *Minerals Sci. Engng.*, 8, 129–169.

MILLMAN, A.P., 1957. Biogeochemical investigations in areas of copper-tin mineralization in South-west England. *Geochim. Cosmochim. Acta*, 12, 85–93.

MOH, G.H., 1977. Ore minerals. *N. Jb. Miner. Abh.*, 131, 1–55.

MULLIGAN, R., 1962. Origin of lithium and beryllium bearing pegmatites. *Bull. Canadian Min. Metall.*, 55, 844–847.

MULLIGAN, R., 1975. Geology of Canadian tin occurrences. *Geol. Surv. Canada Econ. Geol. Rept*, 28, 155 p.

NAKAMURA, T., 1970. Mineral zoning and characteristic minerals in the polymetallic veins of the Ashio copper mine. *In* Tatsumii T., ed., "*Volcanism and Ore Genesis*", Univ. Tokio Press, Tokyo, 231–246.

NAKAMURA, T. and Hunahashi M., 1970. Ore veins of Neogene Volcanic Affinity in Japan. *In Volcanism and Ore Genesis.* Ed. Tatsumi, T., Univ. Tokio Press, Tokyo, 215–230.

NEIVA, J.M.C., 1944. *Jazigos Portugueses de cassiterite e de wolframite.* Empresa Indust. Grafica do Porto, Lda. 251 p.

NIKULIN, N.N., 1967. The distribution of indium, niobium and scandium in the cassiterites of the Khingan deposit. *Vest. Leningr. gos. Univ. (Geol. Geogr.)* 6, 81–87. [English abstract, 1969, *Min. Abs.*, 20, 108].

NICHOLDS, S.R., 1966. The behaviour of some elements during fractional crystallisation of magma. *Geochim. Cosmochim. Acta*, 30, 267–278.

ONISHI, H. and Sandell, E.B., 1957. Meteoric and terrestrial abundance of tin. *Geochim. Cosmochim. Acta*, 14, 262–270.

ONTOEV, D.O., 1974. *The stage character of mineralization and zoning of the deposits of Transbaikalia.* Nauka, Moscow. (In Russian).

PARK, C.F. and MacDiarmid, R.A., 1970. *Ore deposits.* Freeman and Co., San Francisco. 522 p.

PEREIRA, J., 1963. Reflections on ore genesis and exploration. *Mining Mag.*, 108, 9–22.

PEREIRA, J. and Dixon, C.J., 1965. Evolutionary trends in ore deposition. *Trans. Instn. Min. Metall.*, 74, 505–527.

POCKLEY, R.P.C., 1963. Four new uranium-lead ages from Cornwall(Abs) *Notice No. 125, Min. Soc., Lond.*

RAMDOHR, P., 1950. *Die Erzmineralien und ihre Verwachsungen.* Akademie Verlag, Berlin, 827 p.

RINGWOOD, A.E., 1955a. The principles governing trace element distribution during magmatic crystallisation. Part I. The influence of electronegativity, *Geochim. Cosmochim. Acta*, 7, 189–202.

RINGWOOD, A.E., 1955b. The principles governing trace element behaviour during magmatic crystallisation. Part II. The role of complex formation. *Geochim. Cosmochim. Acta.*, 7, 242–254.

ROUTHIER, P., 1969. Sur trois principles generaux de la metallogenie et de la recherche minerale. *Mineral. Deposita (Berl.)*, 4, 213–218.

SAINSBURY, C.L., 1964. Geology of the Lost River mine area, Alaska. *Bull. U.S. Geol. Surv.*, 1129.

SAINSBURY, C.L., and Hamilton, V.C., 1968. The geology of lode-tin deposits. *A technical conference on tin. London, 1967.* I.T.C., 313–349.

SANTOKH SINGH, D. and Bean, J.H., 1968. Some general aspects of the minerals in Malaysia. In '*A technical conference on tin. London, 1967.* I.T.C., London, 459–478.

SAROSIEK, J. and Klys, B., 1964. The tin content in plants and soil in Sudety. *Acta. Soc. Botan. Polan.*, 31, 737. Also in *Chem. Abstr.*, 60, 1645lh (1964).

SALTRAN, V. and Klominsky, J., 1970. Petrometallogenic series of igneous rocks and endogenous ore deposits in the Czechoslavak part of the Bohemaian Massif. *Sbor. Geol. Ved., R. LG*, 12, 65–154.

SAWKINS, F.J., 1966. Preliminary fluid inclusion studies of the mineralization associated with the Hercynian granites of Southwest England. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*,75, B109–B112.

SCHUILING, R.D.. 1968. Tin belts around the Atlantic Ocean: Some aspects of the geochemistry of tin. "*A technical conference on tin: London*". I.T.C., London, 531–547.

SCRIVENOR, J.B., 1928. *The geology of Malayan ore-deposits.* Macmillan & Co., Ltd., London. 206 p.

SILLITOE, R.H., 1972. Relation of metal provinces in western America to subduction of oceanic lithosphere. *Bull. Geol. Soc. America*, 83, 813–818.

SILLITOE, R.H., Halls, C. and Grant, J.N., 1975. Porphyry tin deposits in Bolivia. *Econ. Geol.*, 70, 913–927.

SLATKINE, A., 1966. Cassiterite metasomatique de Muhurgwe. *Bull. du Service Gèologique, Republique Rwandaise*, no. 3, 43–46.

SMITH, F.G., 1947. Transport and deposition of the non-sulphide vein materials, 2. Cassiterite. *Econ. Geol.*, 42, 251–264.

SÓHNGE, P.G., 1963. Genetic problems of pipe deposits in South Africa, *Proc. Geol. Soc. S. Africa*, 66, 19–72.

STEMPROK, M., 1977. The source of tin, tungsten, and molybdenum of primary ore deposits. *Metallization associated with acid magmatism*, 2. Geol. Surv. Prague, Czechoslovakia, 127–166.

STEMPROK, M. and Skvor, P., 1974. Composition of the tin-bearing granites from the Krusne Hory metallogenic province of Czechoslovakia. *Sbor. geol. Ved. R.G.*, 16, 7–87.

STEVENSON, B.G.and Taylor, R.G., 1973. Trace element content of some cassiterites from Eastern Australia. *Proc. Roy. Soc. Queensland.*, 84, 43–54.

STRAUSS, C.A., 1954. The geology and mineral deposits of the Potgietersrus tinfields. *Mem. Geol. Sury., South Africa*, 46, 252p.

TAUSON, L.V., 1967. Factors of the geochemical history of rare elements in a granite-magmatic process. *Geokhimiya*, 1310–1319. (In Russian) TAYLOR, R.G., 1966. Distribution and deposition of cassiterite at South Crofty mine, Cornwall. *Trans. Instn. Min. Metall.*, 75, B35–B49.

TAYLOR, R.G., 1969. Influence of early quartz-feldspar veins on cassiterite distribution at South Crofty Mine, Cornwall. *Trans. Instn. Min. Metall.*, 78, B72–B75.

TAYLOR, R.G., 1974. Contribution to the paper by Hosking, K.F.G., 'The search for deposits from which tin can be profitably recovered now and in the forseeable future'. *Fourth world conference on tin. Kuala Lumpur, 1974.* I.T.C., 79.

TAYLOR, R.G., 1974. Metallogenic provinces as an approach to the problems of classification and genesis of tin deposits with special reference to E. Australia. *In* Stemprok, M., Ed., "*Metalization associated with acid magmatism,*" Geol. Surv. Czechoslovakia. 71–78.

TAYLOR, R.G. and Stevenson, B.G., 1972. An analysis of metal distribution and zoning in the Herberton Tinfield, North Queensland, Australia. *Econ. Geol.*, 67, 1234–1240.

TISCHENDORF, G., 1977. Geochemical and petrographic characteristics of silicic magmatic rocks associated with rare-element mineralization. "*Metallization associated with acid magmatism, 2,*" Geol. Surv. Prague, Czechoslovakia, 41–96.

TURNEAURE, F.S., 1960. A comparative study of major ore deposits of Central Bolivia. *Econ. Geol.*, 55, 217–254 and 574–606.

UDODOV, P.A. and Parilov, Yu. S., 1961. Certain regularities of migration of metals in natural waters. *Geochemistry*, 8, p 763.

VARLAMOFF, N., 1949. Relation entre les facies des cristaux de cassiterite et la geologie de leurs gisenments. *Ann. Soc. Geol. de Belg.*, 72, 289–310.

VARLAMOFF, N., 1972. Central and West African rare-metal granitic pegmatites, related aplites, quartz veins and mineral deposits. *Mineral. Deposita (Berl.)*, 7, 202–216.

VARLAMOFF, N., 1975. Classification des gisements d'etain. *Academie royale des Sciences d'Outre-Mer.*, 14–5, Bruxelles, 63 p.

VERSCHURE, R.H. and Bon, E.H., 1972. Geology and geochronology of tin-bearing volcano-plutonic complexes in Rondonia (Western Brazil). *Reflections report, Z.W.O. Laboratorium voor Isotopen Geologie*, 177–198.

WAGHORN, J.W., 1973. Granites and tin mineralisation in Rondonia, Western Brazil. *Detritus.* (The Mennell Society Journal), University of Rhodesia, 8, 29–34.

WATSON, J., 1973. Influence of crustal evolution on ore deposition. *Trans. Instn. Min. Metall., Section B*, 82, B107–B113.

WEDEPOHL, K.H., 1969. *Handbook of geochemistry*, 2, pt. 1, Springer-Verlag, 50-B-1–50-M-1.

WHITE, D.E. and Waring, G.A., 1963. Volcanic emanations. Chapter K in *Data of Geochemistry*, (6th ed), U.S. Geol. Surv. Prof. Paper 440-K.

ZHILINSKII, G.B., 1959. The tin-bearing granites of Central Kázakhstan (in Russian)—Alma-Ata.